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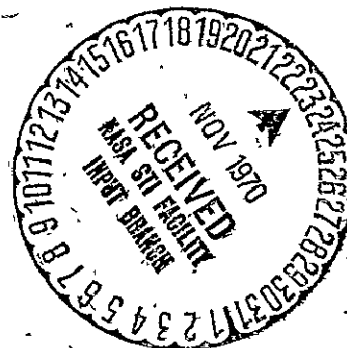
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# ENGINEERING-ECONOMIC ANALYSIS OF THE TDRS K<sub>U</sub>-BAND GROUND ANTENNA SYSTEM

ANDREW J. ROLINSKI

SEPTEMBER 1970



**GSFC**

**GODDARD SPACE FLIGHT CENTER**

**GREENBELT, MARYLAND**

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Andrew J. Rolinski

September 1970

Goddard Space Flight Center  
Greenbelt, Maryland

## PREFACE

Goddard Space Flight Center (GSFC) manages and operates two National Aeronautics and Space Administration (NASA) tracking and data-acquisition networks, viz., Space Tracking and Data Acquisition Network (STADAN) and Manned Space Flight Network (MSFN). Increase in the requirements for telemetry data and data rate and the extension of the life of scientific and manned spacecrafts have increased the workload of the STADAN and MFSN stations; it is anticipated that the network workload will continue to grow in the future. Concurrently, operating budgets for the networks are being reduced. These circumstances motivated GSFC management to conduct several studies on the concept of a tracking and data relay satellite (TDRS) system. Studies have indicated that the TDRS concept is technically feasible and economically practical. Basically, TDRS is a geostationary relay link which performs major network functions while orbiting the earth.

Various ways of implementing the TDRS scheme have been suggested. One of the more attractive schemes includes the installation at GSFC of a 16 GHz ( $K_u$ -Band) antenna system that has a data bandwidth capability of two GHz. To engineer such a ground station involves new subsystem development and a critical evaluation of all key design factors. To analyze the system from the engineering management viewpoint, i.e., to determine the optimum cost effectiveness solution, requires a comparable effort.

Broadly speaking this study is a systems analysis of three competing TDRS ground station configurations. These configurations are the following:

- (1) the single dish (SD) ground station; a large reflector mounted on a single pedestal,

(2) the quad-array (QA) ground station; an array of four reflectors mounted on a single pedestal, and

(3) the multiple-aperture (MA) ground station; an array of four reflectors each mounted on a separate pedestal.

The core of the study involves the determination of TDRS ground station cost-effectiveness values. The procedure is as follows:

(1) study of the critical system design parameters, which include factors of availability, antenna gain limit and reflector surface tolerance, system noise temperature and the environmental influence.

(2) parametric analysis of the key design elements to develop the appropriate system effectiveness (level of performance) criterion;

(3) development of appropriate cost models for the three station configurations;

(4) trade-off analysis to determine the cost-effectiveness order of preference for the configurations examined.

The focus of the investigation is on systems analysis of the basic ground antenna design only. That is, only costs related to the antenna systems and the associated electronics are considered. The analysis does not include total costs of station installation, costs related to the TDRS development or costs associated with the launch of a TDRS. To analyze in-depth the total TDRS network operation, would require at least an order of magnitude more manpower effort than the individual effort which was applied to the study.

Nevertheless, it is impossible to prepare an analysis of this sort without assistance from my coworkers. I owe special thanks to Leonard F. Deerkoski for significant suggestions and illustrative material.

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## ACRONYMS USED IN THE TEXT

ATS	- Applications Technology Satellite
BEP	- Break Even Point
bps	- Bits per second
CNR	- Carrier-to-Noise-Ratio
db	- Decibel - a dimensionless unit, the ratio of power or gain
dbm	- Ratio of Power with respect to one milliwatt
dbw	- Ratio of Power with respect to one watt
DRSCON	- TDRS Satellite Control Center
DRSNET	- TDRS Network Control Center
EIRP	- Equivalent Isotropic Radiated Power
ERTS	- Earth Resources Technology Satellite
GHz	- Frequency Giga Hertz ( $10^9$ cycles per second)
GRARR	- Goddard Range and Range Rate
GSFC	- Goddard Space Flight Center, Greenbelt, Maryland
HDR	- High-Data-Rate
Hz	- Frequency, Hertz (cycles per second)
JPL	- Jet Propulsion Laboratory, Pasadena, California
°K	- Degrees Kelvin
Kbps	- Kilobits per second
K <sub>u</sub> -Band	- Operating radio band (16 GHz)
LDR	- Low-Data-Rate
MCC	- Mission Control Center
MFSN	- Manned Flight Space Network
MHz	- Frequency, Mega Hertz ( $10^6$ cycles per second)

MSC	- Manned Spacecraft Center, Houston, Texas
NASA	- National Aeronautics and Space Administration
NASCOM	- NASA Communication System
NETCON	- STADAN Network Control Center
NF	- Receiver Noise Figure
OAO	- Orbiting Astronomical Observatory
PCM	- Pulse-Coded Modulation
PN	- Psuedonoise
RF	- Radio Frequency
RFI	- Radio Frequency Interference
S-Band	- Operating radio band (1750 to 2300 MHz)
STACON	- TDRS Ground Station Operations Control Center
STADAN	- Space Tracking and Data Acquisition Network
TWTA	- Traveling Wave Tube Amplifier
USB	- Unified S-Band
VHF	- Very High Frequency (136-150 MHz)
X-Band	- Operating radio band (7-8 GHz)

## INTRODUCTION

Successful technical management depends importantly on the ability of the engineering manager to supplement technical skills with the best of new management tools and particularly, the implement of systems analysis. According to Van Court Hare, Jr., the purpose of systems analysis is the management and control of variety before variety controls and manages the manager.<sup>1</sup> It provides a factual basis for rational decision making.

Systems analysis has been defined as an analytical approach to the study of complex problems and is designed to help a manager identify a preferred course of action from among possible alternatives.<sup>2</sup> It involves a systematic procedure of searching out objectives and alternatives and comparing them, within an analytical framework, to help bring expert judgement and intuition to bear on a system problem. The systems analysis structure contains five distinct elements; these elements are as follows:

- (1) Objective(s) - the desired goal;
- (2) Alternatives - the competitive systems for achieving the goal;
- (3) Costs - the resources that must be expended to achieve the goal;
- (4) Model - the representation quantitatively (mathematically) of the real system;  
and,
- (5) Criterion - the standard of performance for the system.

---

<sup>1</sup>Van Court Hare, Jr., Systems Analysis: A Diagnostic Approach (New York: Harcourt, Brace and World, Inc., 1967) p. 9.

<sup>2</sup>Edward S. Quade and W. I. Boucher, ed., Systems Analysis and Policy Planning: Applications in Defense (New York: American Elsevier Publishing Co. Inc., 1968) p. 2.

In applying the systems analysis philosophy to the development of a ground antenna system associated with the Tracking and Data Relay Satellite (TDRS) Network, a modification to the above structure is required. In this study, the analytical framework that is more meaningful in regards to the TDRS ground station design will contain the following elements:

(1) Ground Station Operational Requirements - the technical requirements of the system based on projections for network support and on the future schedule of space missions;

(2) Development of an Effectiveness Model - the derivation of a standard in system performance

(3) Development of Cost Models - the mathematical representation of system costs for the various competing systems considered;

(4) Trade-Off (Cost Sensitivity) Analysis - the procedure to develop a ranking of various alternatives in the order of their relative cost effectiveness values.

The framework described above is illustrated in Figure 1, Relationships of Models in the Analysis of a Ground Antenna System.

As a way of understanding the system and grasping the size of the system problem, a brief technical discussion of TDRS will follow.

Historically, the Tracking Data Relay Satellite (TDRS) was conceived as a communication system using several spacecraft located in earth-synchronous orbits to permit two-way communications service between near-earth space vehicles and strategically located control centers. Advancements in space technology, however, permitted the TDRS concept to be enlarged to include a broad range of communications functions and data relay services. The TDRS concept that will be examined uses geostationary

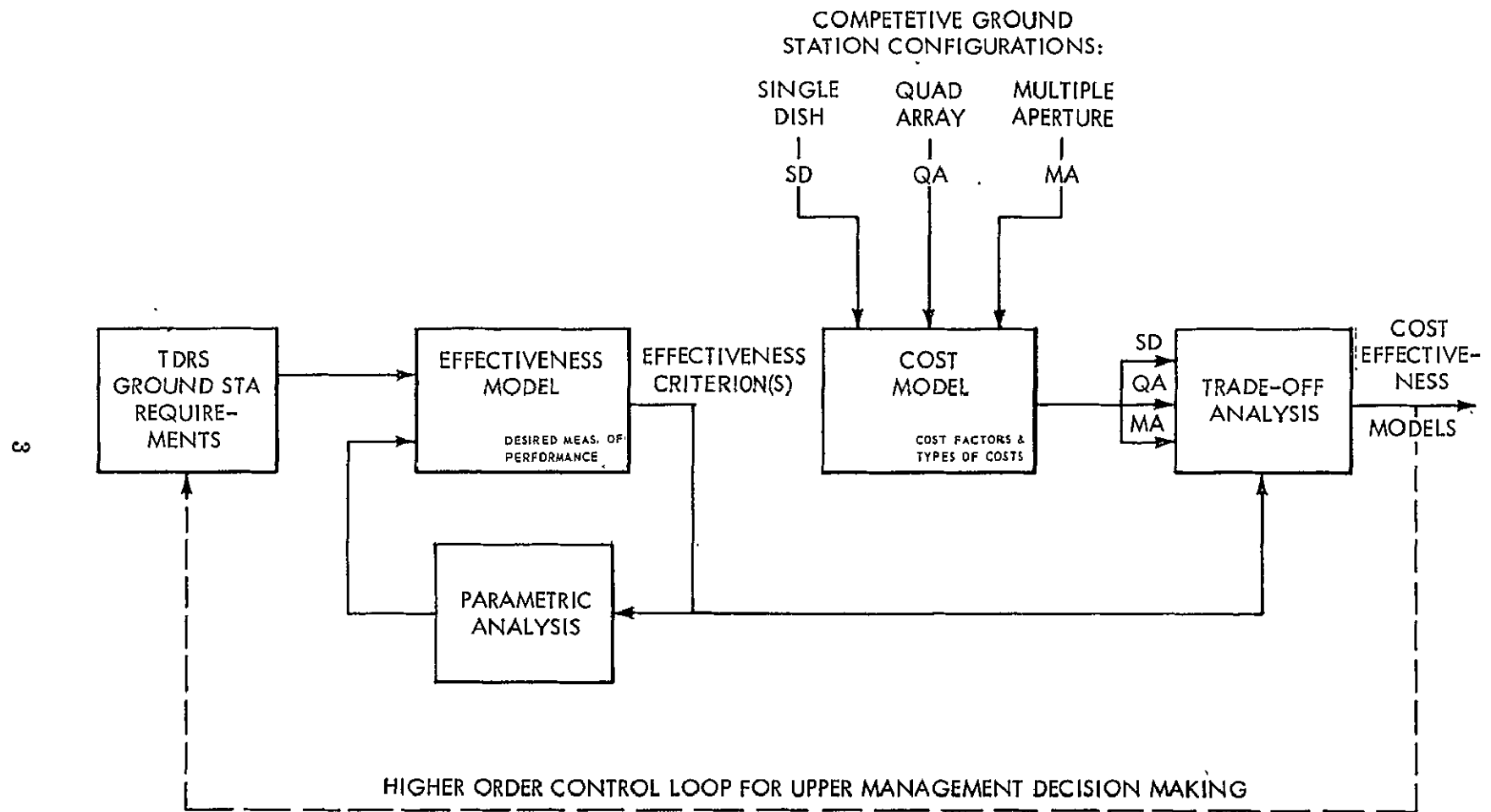


Figure 1. Relationships of Models in the Analysis  
of A Ground Antenna System.

spacecraft to command, track and relay data from multiple low earth-orbiting satellites to a single ground station located at Goddard Space Flight Center (GSFC).

The essential purpose of the TDRS system is to establish an economically feasible network system for using synchronous orbiting satellites in conjunction with the single ground site to provide full global coverage and network operations that would include real time command and efficient data recovery. The implementation of TDRS may result in reducing costs and/or improving tracking systems effectiveness and the establishment of a new telecommunications service which would provide continuous real time access to user spacecraft<sup>3, 4</sup>; see Figure 2 for illustration of the concept.

The salient technical objectives of the TDRS system are as follows:

- (1) support of all missions with orbits up to 8000 kilometers (5000 miles) above the Earth and at all orbital inclinations;
- (2) support twenty to forty low-data-rate (LDR) users, ten medium data-rate (MDR) users and up to four high data-rate (HDR) users; and,
- (3) for manned space flight programs, the support of two vehicles simultaneously, for example, Skylab and Space Shuttle, at all inclinations.<sup>5</sup>

To achieve the above objectives the ground station related to the TDRS will be required to handle wide band data link 2GHz wide. It is assumed that the highly directional  $K_u$ -band ground link can be readily established, thereby restricting the frequency of operation of the ground antenna to the  $K_u$ -band region. Specifically, the region of operation will be between 15.7 and 17.7 GHz.

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<sup>3</sup>Tracking and Data Relay Satellite Network (TDRSN), Final Study Report, (Pasadena, Calif.: Jet Propulsion Laboratory, September, 1969) p. 1-1.

<sup>4</sup>GSFC Mark 1 Tracking and Data Relay Satellite (TDRS) System Concept, Phase A Study Final Report, Vol. 1 (2 Vols. Greenbelt, Md.: Goddard Space Flight Center, Nov. 1969), p. 1-1.

<sup>5</sup>Ibid, p. 3-3.



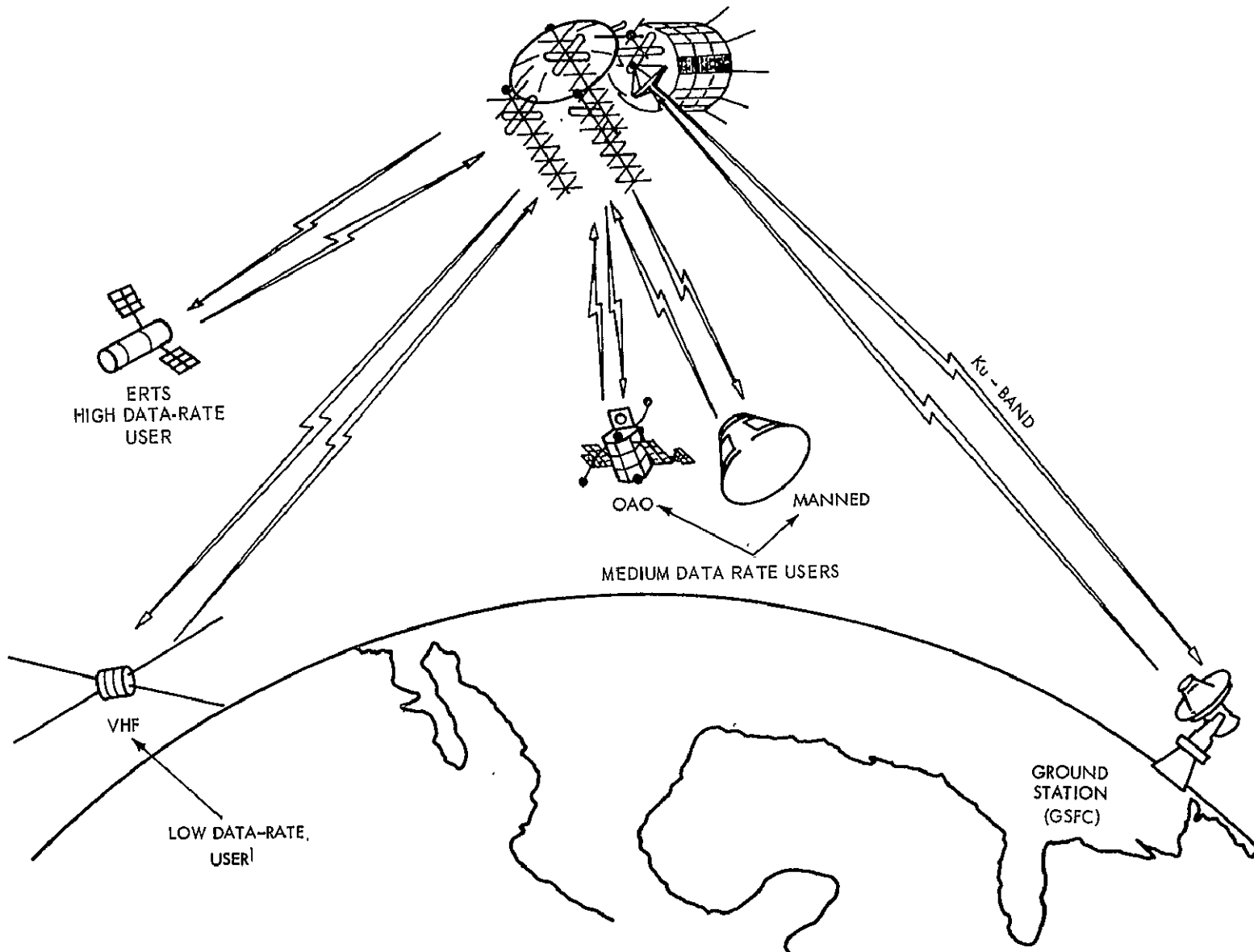


Figure 2. Tracking and Data Relay Satellite Concept.

The overall concept of the ground terminal will include equipment capable of meeting the following functional requirements:<sup>6</sup>

(1) Command, or uplink data relay - The TDRS will relay command signals to the user spacecraft by converting a 17.7 GHz command signal from the ground station.

(2) Data relay - The wide band data (video) and narrow band data received from user spacecraft by a TDRS, will be transmitted to the ground station on a 15.7 GHz downlink.

(3) Tracking from one TDRS - Range and range rate tracking signals for all user spacecraft will originate and terminate at the ground station. These signals will be sent to and received from the TDRS spacecraft on  $K_u$ -band. The TDRS will not process the signals but will relay them to and from user spacecraft at the appropriate frequencies.

(4) Dual tracking (from two TDRS) - A single ground station will accommodate simultaneous range and range rate tracking of user spacecraft from two TDRS spacecraft.<sup>#</sup> This requires two separate  $K_u$ -band links, one to each TDRS.

(5) Emergency communication service - The very high frequency (VHF) telemetry link will be maintained almost continuously, by using the supporting VHF stations, from before launch through initial  $K_u$ -band operations in synchronous orbit. VHF commands may be transmitted from many of the existing STADAN stations. After  $K_u$ -band link up between TDRS and ground station occurs, the VHF link could provide a back-up (emergency) mode for TDRS telemetry and command.<sup>7</sup>

In short, the ground station electronic equipment will be capable of receiving and transmitting wide variety of signals, from wideband video to housekeeping data, originate and process tracking signals, and provide full communication service.

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<sup>6</sup>Ibid, p. 9-5.

<sup>7</sup>Ibid, p. 9-7.

Figure 3 depicts the equipment and the data flow at the TDRS ground station. The configuration assumes a single 97-foot antenna as the basic radio element in the ground system.

The above technical description is by no means complete. The many configurations and possible combinations of systems that could be analyzed are beyond the scope of this investigation. For a tractable analysis the study will be confined to three possible configurations which are considered most probable by a body of experts and the managers who planned the concept and will ultimately decide how it will be implemented.

Thus, by axiom of choice, the three configurations to be studied are the following:

- (1) Single antenna station, located at Goddard with or without a radome.
- (2) Array of antennas, located at Goddard.
- (3) An array of apertures, nested on a single pedestal, located at Goddard.

Furthermore, the analysis must be limited in the number of functional requirements which can be studied and the number of system parameters which can be analyzed and manipulated. If the functions that are studied are the crux of the TDRS operation and further, assuming the parameters that are considered are critical to gain an understanding of the behavior of the system, the analysis can then be considered fruitful and will aid the decision makers in their cogitative process to select the "best" ground station configuration for the money available.

One further assumption should be mentioned prior to the start of the systems analysis. It is truly the key assumption because all others rely on it. It is assumed that the rationale to establish a TDRS system has been accepted and the concept is

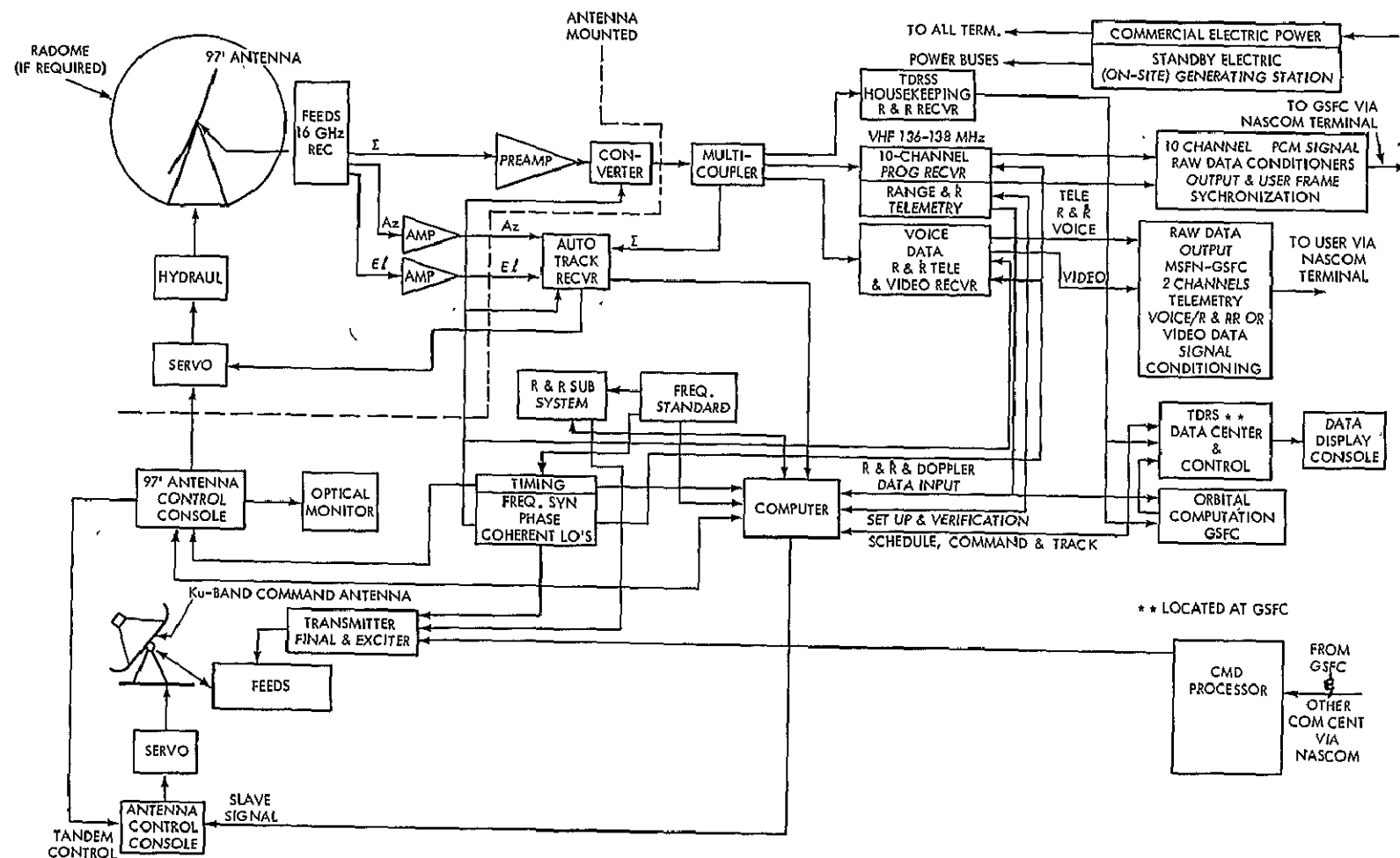


Figure 3. Typical TDRS Tracking Station (Single-Antenna Configuration)

considered economically and technically feasible.<sup>8,9</sup> The investigation is directed to establishing cost effectiveness models of the three ground station configurations and developing the *raison d'être* for the ranking of the various models.

The subject matter is divided into two parts. Part one, consists of formulation of the problem to be studied; this part includes the establishment of the basic framework of the study in terms of objectives, assumptions, constraints and critical ground station parameters. Part two, is the essence of the study; it involves the establishment of a hierarchy of systems in order of preference from the standpoint of system cost-effectiveness. In part two, Chapter 3, the effectiveness model is first developed; then in Chapter 4, the cost models are constructed. The basic evaluation takes place in Chapter 5 in the form of a trade-off analysis. Chapter 6 presents additional aspects considered in the analyses and summarizes the results of the study.

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<sup>8</sup>Edmund J. Habib, T&DS Mission Model and Projected Spacecraft Support Requirements Through 1980 (Greenbelt, Md.: Goddard Space Flight Center X-520-69-110, March 1969) p. 4.

<sup>9</sup>Leonard F. DeerKoski, Howard Estep, Paul A. Lantz and Nicholas A. Raumann, K<sub>u</sub>-Band Tracking and Data Relay Satellite Ground Antenna Study (Greenbelt, Md.: GSFC X-525-70-200, June 1970) pp. 3-1, 3-2, 3-3, 3-4.

## SUMMARY OF RESULTS

The basic findings ~~which resulted from this study~~ are the following:

(1) The limiting factor in the process of detecting electromagnetic energy is thermal noise. Thus, noise temperature of the system is a critical system parameter. Since the noise figure (NF) of the receiver is a measure of its noise contribution to the system, the NF of the preamplifier is closely related to the system noise temperature. It was found that receivers with cooled paramp preamplifiers can achieve a 25 per cent reduction in system noise temperature; and, for equal antenna effectiveness, the implied reduction in cost is approximately 35 per cent.

(2) Weather conditions adversely affect antenna performance at Ku-band. For example, in heavy rainfall it is possible for the antenna to have its gain reduced by a factor of 25 over the gain that is ordinarily achievable under clear sky conditions.

(3) For a given operating frequency, the reflector surface tolerance limits the gain of the antenna. For the cost model developed, decreasing the tolerance, increases the costs of the antenna in an exponential manner.

(4) Radomes are considered poor choices from the cost effectiveness viewpoint. Not only does performance of a radome-enclosed antenna degrade drastically with heavy rainfall, but, also, the normally assumed 20 per cent loss due to radome absorption requires a 55 per cent increase in antenna area, when the antenna is operating near its gain-limit point, to achieve an effectiveness equal to that of an exposed antenna.

(5) For a system gain requirement of 70 db, the preferred cost effectiveness antenna is the quad-array (QA). It will be shown that the smaller-sized antennas operate

more efficiently. Furthermore, because of the number of antennas involved, the total system mean-down-time is reduced to virtually zero. Thus, the QA antenna can be made almost 100 per cent available.

(6) For a system gain requirement of 68.5 db, the "best" cost-benefit station is the single dish (SD) station. Since the costs related to operation and equipment replacement are significant weighting factors in the cost-benefit study, the array systems do not compare as favorably as the SD system in this analysis. ~~However, as it will be~~ shown in the text, when other than economic factors are also considered, the QA system becomes as serious a candidate for the "best" position as the SD system for this particular system gain requirement.

A pictorial summary of the analyses are given in Figures 4 and 5. Figure 4 shows the results of the cost-effectiveness analysis and Figure 5 depicts the results of the economic (cost-benefit) analysis.

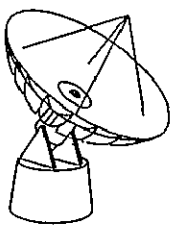
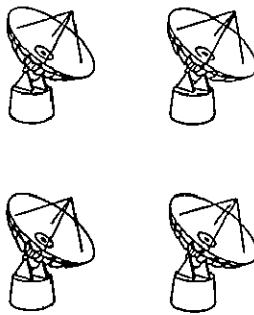
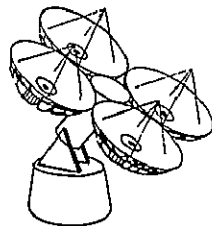
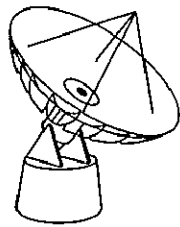
					
SINGLE APERTURE		MULTI-APERTURE ARRAY SEPARATE PEDESTALS		MULTI-APERTURE ARRAY COMMON PEDESTAL (QUAD-ARRAY)	
68.5 db Gain System	70.0 db Gain System	68.5 db Gain System	70.0 db Gain System	68.5 db Gain System	70.0 db Gain System
1. Cost of Antenna (less electronics) (77 ft. diam.) $\$0.960 \times 10^6$	1. Cost of Antenna (less electronics) (97 ft. diam.) $\$1.870 \times 10^6$	1. Cost of Antenna (less electronics) (4-36 ft. Diam.) $\$1.41 \times 10^6$	1. Cost of Antenna (less electronics) (4-42 ft. diam.) $\$1.64 \times 10^6$	1. Cost of Reflector (4-36 ft. diam) $\$0.496 \times 10^6$	1. Cost of Reflector (4-42 ft. diam.) $\$0.575 \times 10^6$
2. Cost of Electronics (0.5 db NF) $\$0.210 \times 10^6$	2. Cost of Electronics (1.0 db NF) $\$0.195 \times 10^6$	2. Cost of Electronics (0.5 db NF) $\$0.983 \times 10^6$	2. Cost of Electronics (1.0 db NF) $\$0.925 \times 10^6$	2. Cost of Preamp (0.5 db NF) $\$0.288 \times 10^6$	2. Cost of Preamp (1.0 db NF) $\$0.235 \times 10^6$
				3. Cost of Tracking Receiver $\$0.160 \times 10^6$	3. Cost of Tracking Receiver $\$0.160 \times 10^6$
				4. Cost of Pedestal $\$0.715 \times 10^6$	4. Cost of Pedestal $\$0.950 \times 10^6$
Total Cost $\$1.17 \times 10^6$	Total Cost $\$2.065 \times 10^6$	Total Cost $\$2.393 \times 10^6$	Total Cost $\$2.565 \times 10^6$	Total Cost $\$1.659 \times 10^6$	Total Cost $\$1.92 \times 10^6$

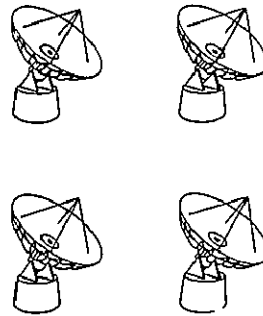
Figure 4. Summary of Results of the Cost-Effectiveness Analysis



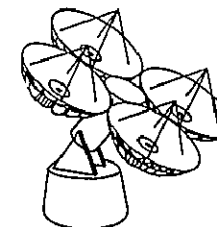


SINGLE APERTURE

68.5 db Gain System	70 db Gain System
1. Total Antenna System Costs (includes command system) $\$1.987 \times 10^6$	1. Total Antenna System (with command system) $\$2.867 \times 10^6$
2. Total Operation & Equipment Costs per annum $\$0.449 \times 10^6$	2. Annual Operation & Equipment Costs $\$0.622 \times 10^6$
3. Present Worth (PW) $\$5.407 \times 10^6$	3. PW - $\$7.597 \times 10^6$
4. Equivalent Annual Cost (EAC) $\$0.713 \times 10^6$	4. EAC - $\$1.004 \times 10^6$

MULTI-APERTURE ARRAY  
SEPARATE PEDESTALS

68.5 db Gain System	70 db Gain System
1. Total Antenna System Costs (includes command system) $\$3.14 \times 10^6$	1. Total Antenna System Costs (includes command system) $\$3.3 \times 10^6$
2. Total Operation & Equipment Costs per annum $\$0.749 \times 10^6$	2. Annual Operation & Equipment Costs $\$0.776 \times 10^6$
3. PW - $\$8.84 \times 10^6$	3. PW - $\$9.2 \times 10^6$
4. EAC - $\$1.167 \times 10^6$	4. EAC - $\$1.215 \times 10^6$

MULTI-APERTURE ARRAY  
COMMON PEDESTAL  
(QUAD-ARRAY)

68.5 db Gain System	70.0 db Gain System
1. Total Antenna System Costs (includes command system) $\$2.39 \times 10^6$	1. Total Antenna System Costs (with command system) $\$2.65 \times 10^6$
2. Annual Operations & Equipment Costs $\$0.546 \times 10^6$	2. Annual Operation & Equipment Costs $\$0.593 \times 10^6$
3. PW - $\$6.54 \times 10^6$	3. PW - $\$7.16 \times 10^6$
4. EAC - $\$0.864 \times 10^6$	4. EAC - $\$0.945 \times 10^6$

Figure 5. Summary of Results of the Cost-Benefit Analysis

## PART I - PROBLEM FORMULATION

### CHAPTER 1

#### OBJECTIVE AND SCOPE OF THE STUDY

One objective of this study is to develop cost effectiveness models for various ground stations considered for the TDRS system. It has been noted that cost effectiveness analysis seeks to increase value received (effectiveness) for the resources expended (cost).<sup>10</sup> Usually cost effectiveness analysis attempts to answer the following question; given a measure of effectiveness, does the cost of the system warrant its implementation?

In the broader context of system analysis, however, the analytical framework not only takes in the cost effectiveness analysis but trade-off analysis as well. Trade-off analysis seeks to compare the benefits of one approach with respect to the benefits of another approach. Thus, the systems analysis methodology gives the manager a quantitative basis to apply seasoned reasoning and technical insights to systems problems. The full objective of this investigation encompasses the tasks of determining the cheapest ground station configuration that can do the required job.

The scope of the study will be constrained by the following assumptions:

- (1) Research and development (R&D) costs will not be included except where imputed costs into new equipment can be readily ascertained.
- (2) The basic ground network configuration will consist of a single site located at GSFC.

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<sup>10</sup> Edward S. Quade and W. I. Boucher, ed., Systems Analysis and Policy Planning: Applications in Defense (New York: American Elsevier Publishing Co. Inc., 1968) p. 17.

(3) The TDRS system will be capable of a TDRS-to-TDRS communication function; thus, no overseas sites will be considered.

(4) The study of costs related to the TDRS development and to the TDRS launch will not be considered in this effort.

(5) The lifecycle of the TDRS ground antenna system will be 15 years.

(6) The three-satellite geometry will be oriented so that the station located at GSFC will always have two satellites in its field of view at any time.

(7) Sufficient directivity will be built into the TDRS-to-ground station link to disregard interference from a diffused scatter (multipath) signal.

To set the yardstick for the system effectiveness criterion, the following technical performance requirements are to be incorporated into the ground antenna system:

(1) an overall antenna availability factor of 0.998; and

(2) A carrier-to-noise ratio (CNR), for 99.8 per cent of the operational time, of 30 decibels (db).

The requirement of 30 db CNR is for "worst-case" operating conditions; it contains a 10 db cushion which takes into account operation under adverse atmospheric conditions.

To limit the size of the study, three practical  $K_u$ -band antenna models will be considered. These are as follows:

- Single Dish (SD) System - One reflector on one pedestal,
- Quad-Array (QA) system - Four reflectors on one pedestal, and
- Multiple-Aperture (MA) System - Four reflectors on four pedestals.

In summary, the basic objectives of the investigation are: to develop a measure of effectiveness for the TDRS ground station to analyze costs associated with three candidate station configurations; and, to establish an order of preference of cost effectiveness models under required operating conditions.

## CHAPTER 2

### GROUND STATION REQUIREMENTS

The fundamental limitations and the extent of the study were outlined in Chapter 1. In Chapter 2, pertinent details of the basic ground station requirements will be described. The purposes of this chapter are: to establish the grounds for plausible assumptions so that subsequent analyses pertaining to costs and trade-offs can be firmly based, and to identify key variables so that the effectiveness model can be properly developed.

The ground station requirements are divided into two types: the functional requirements, i.e., requirements related to functions the station must perform as part of the TDRS network and the performance requirements, i.e., requirements related to the operation of the antenna in accordance to system specifications.

#### 2.1 Functional Requirements

In discussing the functional requirements of the TDRS ground station, the attention will be focused on the interrelationship between the station and the following major functions:

- (1) tracking,
- (2) command, and
- (3) MSFN and STADAN compatibility.

Tracking: The tracking capability of the ground antenna is a primary design consideration because the TDRS ground station will be responsible for range and range rate tracking of all user spacecraft. In the case of a single tracking function, i.e., tracking through one TDRS, the ground station will transmit to the TDRS a carrier that is phase modulated with a pseudo-noise (PN) code. After frequency conversion, the signal is radiated to the user spacecraft. The user transponder phase-locks to the carrier and correlates the PN code. On the return route, the user phase-locked oscillator generates a carrier which is coherent with the received signal. This carrier is similarly modulated by a PN code but at a higher rate. The user spacecraft transmits this signal to the TDRS which once again converts the signal and transmits it to the ground receiver station. By phase-locking the receiver oscillator to the carrier, the two-way Doppler can be extracted for range-rate information and by locking the receiver signal to the PN code, the total path delay can be extracted for range determination.<sup>11</sup>

Nominally, the systems will provide for simultaneous tracking of one or more users. Range and range rate tracking of the TDRS will be accomplished at the same time that user spacecraft are being tracked.<sup>12</sup>

In the case of the dual tracking function, i.e. tracking through two TDR's, the ground station will require two separate data links, one for each TDRS.

Command: The TDRS ground station will transmit commands as specified by user mission control centers through the TDRS control centers (DRSNET, DRSCON, and STACON). The very high frequency (VHF) system will use a PN modulated code

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<sup>11</sup>GSFC Mark 1 Tracking and Data Relay Satellite (TDRS) System Concept, Phase A Study Final Report, Vol. 1 (2 VOLS. Greenbelt, Md.: Goddard Space Flight Center, Nov. 1969) p. 7-12, p. 7-13.

<sup>12</sup>Op. cit. Ibid p. 9-6.

and will support many users for voice and low data-rate (LDR) data transmission, i.e. data transmission of less than 10 kilobits per second (kbs). For the high data rate (HDR) users,  $K_u$ -band, transmission on any of the several Goddard Range and Range Rate (GRARR) channels, converted from S-to  $K_u$ -band, will be possible. The  $K_u$ -band uplinks will have at least two modes of operation; these are as follows:<sup>13</sup>

- (1) TDRS housekeeping (status and control) command, and
- (2) GRARR command and tracking signals.

The command capability at  $K_u$ -band will be several million bits per second (M bps); thus, uplink video can be easily accommodated.

Although presently  $K_u$ -band technology is not developed sufficiently to provide several kilowatt command capability, it is believed that for the launch dates considered, 1974-1980 time frame, the technology will be available. This belief is based on a documentation search as well as direct inquiries to a number of system suppliers.<sup>14</sup>

Compatibility With MSFN and STADAN: The development of the TDRS network will impact greatly the MSFN and STADAN networks. For example, for the low-orbiting spacecraft and the manned flight spacecraft, the TDRS system will have to be considered as an integral part of a worldwide network. Since the bulk of the tracking, telemetry and command functions will be handled by a TDRS network having full earth coverage, the existing coverage by MSFN and STADAN stations will not be necessary. Consequently, these network stations will be "thinned-out" when TDRS system becomes operational. For this study, only that reduction in operation and maintenance costs

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<sup>13</sup>Ibid p. 6-141.

<sup>14</sup>Ibid p. 6-149.

will be considered which can be attributed to the basic antenna system investment.

Total costs per station which include site preparation and buildings, power plant and a large amount of multifarious electronic equipment have been taken into account in a study recently concluded at GSFC (see reference 15).

## 2.2 Ground Station Performance Requirements

The ground system is required to meet a particular performance level which can be characterized by the following parameters and operational factors:

- (1) TDRS  $K_u$ -band to ground station link,
- (2) coverage, tracking and command of TDRS,
- (3) ground station reliability, and
- (4) antenna effectiveness.

TDRS  $K_u$ -band to Ground Station Link: The  $K_u$ -band antenna on the TDRS spacecraft will provide the appropriate pattern directivity to achieve the desired ground coverage. A four foot diameter parabolic reflector is assumed. This size has a nominal gain of 43.5 db at 55 percent efficiency. The 3-db beamwidth of this antenna is about one degree. The narrow beamwidth requires that the antenna subsystem mounted on an earth-pointing platform be stabilized to better than 0.20 degrees. The station-keeping subsystem will require a sophisticated control system to accomplish this platform stabilization.

The transmitter power on the spacecraft is assumed to be 20 watts or equivalent isotropic radiated power (EIRP) of 86.5 dbm per channel.

Coverage, Tracking and Command of TDRS: Assuming that the receiving ground antenna is approximately 97 feet in diameter, the 3 db beamwidth at 16 GHz is approximately 0.045 degrees. To reduce the pointing losses of the antenna to an acceptable

level, the antenna should be pointed to within 0.01 degrees of the beam center or approximately a quarter of a beamwidth; the resultant loss is approximately 0.5 db. The servo drive and control subsystem of the antenna must be capable of pointing the antenna to the 0.01 degree figure under all the environmental conditions for which mission support is required. To reduce the tracking loss to 0.1 db would require a servo system that is capable of pointing the antenna with an accuracy of 0.005 degrees or better. This is a stringent requirement and would require an advanced control system design.

The high gain and the large band-width requirements for the receive function of the TDRS ground station imposes a strong need for a broad band, high efficiency receive feed. The addition of the transmit function would seriously compromise the design of the receive feed system. It is, therefore, assumed in this study that the two functions of receive and command will be performed by two separate antenna systems.

Ground Station Reliability: The reliability effectiveness of the TDRS ground antenna system can be stated in quantitative terms. The measure of system reliability effectiveness is defined as availability; for the TDRS ground station, the availability has been set at 0.998. To achieve an availability approaching unity would require ultra reliable equipment and/or an operating duty cycle that would allow preventive maintenance to be performed when the system is operative but temporarily idle.

The steady state probability of system availability can be expressed mathematically as follows:<sup>15</sup>

$$A = \frac{MTTF}{MTTF + D} \quad (1)$$

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<sup>15</sup>Gerald H. Sandler, System Reliability Engineering (Englewood Cliffs, N.J.: Prentice-Hall Publ. Co., 1963) p. 12.



where, A = Steady-State Availability, i.e. the proportion of time that the system is available for use when the time interval considered is large.

MTTF = Mean-Time-to-Failure, i.e. the average time the system is in the operating state; this includes idle time and operating time, it is measured in hours.

D = Mean-Down-Time, i.e. the average time the system is in the failed state, measured in hours.

It should be noted that system outage (SO) is 1-A, i.e., the probability of unavailability. This can be expressed as:

$$SO = \frac{D}{MTTF + D} \quad (2)$$

Clearly, for the above mentioned considerations,  $MTTF \gg D$ , the system outage will approach zero. There are several techniques available to reduce the Mean-Down-Time, D, to very small values, 30 minutes or less. These techniques include using modular construction and applying modern trouble shooting methods.<sup>16</sup>

Antenna Effectiveness: Assuming that the TDRS ground station must operate with a 30 db CNR and be capable of receiving telemetry data on a 2 GHz wide data-channel, the overall antenna effectiveness becomes a sensitive measure of system capabilities. A measure of antenna effectiveness is related to system noise temperature, the antenna gain and efficiency. The formula for antenna effectiveness is given as:

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<sup>16</sup>Van Court Hare, Jr., Systems Analysis: A Diagnostic Approach (N.Y.: Harcourt, Brace and World, Inc. 1967) Chap. 14 pp. 442-446, Chap. 10, pp. 260-272.

$$AE = \frac{\eta}{T_s} \left( \frac{4 \pi A}{\lambda^2} \right) \quad (3)$$

where,

AE = antenna effectiveness in decibels per degree Kelvin (db/°K)

A = aperture area in feet squared

$\eta$  = antenna efficiency, ratio of actual to ideal energy conversion,

$T_s$  = system noise temperature in degrees Kelvin (°K), and

$\lambda$  = wavelength in feet

Equation (3) can be expressed as:

$$AE \approx \frac{\eta G}{NF}$$

Detailed discussion and derivations of the formulas related to AE are given in Appendix A.

Clearly, the variables in the approximation above are G,  $\eta$ , and NF (noise figure). Thus, by increasing antenna efficiency, for given gain, the aperture can be made smaller. Furthermore, by lowering the NF of the preamplifier, the system noise temperature is reduced which in turn increases antenna effectiveness. Thus, a parametric analysis involving aperture size (for a given gain), efficiency (as related to surface tolerance) and noise figure (as related to receiver technology development in  $K_u$ -band) can aid in developing the appropriate effectiveness model for the TDRS ground station. For this study, it will be assumed that the preamplifiers that will be available will have NF's of 1.0 and/or 0.5 db. Literature and expert opinion in the field agree that the  $K_u$ -band hardware will be available for launches beyond 1978.<sup>17</sup>

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<sup>17</sup> Specific features of  $K_u$ -band equipment and actual source documents on  $K_u$ -band technology is classified information.

## PART II - SELECTING THE BEST TECHNICAL APPROACH

### CHAPTER 3

#### DEVELOPMENT OF AN EFFECTIVENESS MODEL

To develop an acceptable effectiveness model, various antenna performance characteristics are examined in parametric form. The main reason for this approach is to establish a scale so that there is some means of determining the technical compliance of each considered alternative. Once a quantitative scale has been established, the degree of acceptability of feasible solutions and the variations or trade-offs that can be made to achieve the desired performance level can be considered in light of costs and system constraints.

#### 3.1 Parametric Analysis

Three basic parameters will be studied. These are:

(1) Availability. The fundamental variables related to antenna availability are weather and equipment reliability. Other important factors that are related to station availability but will not be considered in the trade-off study are the degree of complexity of TDRS network operations, and the amount of logistic support required.

(2) System Noise Temperature. The parameters related to system noise temperature are the following: (a) antenna noise which is due mainly to feed spillover, scattering and resistive loss, (b) sky noise which is dominantly tropospheric and extraterrestrial noise and (c) receiver noise which comes from the receiver noise temperature and transmission line loss.

(3) Gain limits on Reflector Antennas. The basic variables connected with antenna gain limits are: (a) the diameter of the dish or the effective aperture area,

(b) frequency of operation, and (c) root-mean-squared (RMS) error related to surface tolerance and designated as  $\sigma$ .

Availability Factors: It has been assumed that the system must be available 99.8 percent of the time. Availability was defined as the ratio of time the system is in operation to the time the system is in operation plus down time, see equation (1).

The availability of the antenna is adversely affected by disturbances in the propagation medium. Thus, changes in weather are directly related to changes in antenna noise. This results in changes in the carrier-to-noise ratio (CNR). As noise power increases, the CNR decreases. When the CNR is less than 20 db, the system is no longer operating at maximum effectiveness, and when the CNR goes much below the 10 db level, the radio link between the TDRS and the ground station is considered no longer operative.

The antenna noise is not only directly related to prevailing sky conditions but is also related to the elevation angle of the antenna.<sup>18</sup> Table I shows the amount of loss in db and the corresponding noise of the antenna as a function of elevation angle and sky conditions.<sup>19</sup> Thus, the 0.998 availability of the antenna system at 16 GHz for elevation angles much below 15 degrees may be impractical. Assuming that the TDRS ground station would be located in the Washington, D.C. area, the average annual rainfall data from the United States Weather Bureau shows that rain heavier than one

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<sup>18</sup> An elevation angle is measured from the horizon to the zenith. Zero elevation angle means that the line-of-sight (LOS) of the antenna is parallel to the ground line (i.e., antenna is pointing at the horizon) and as the elevation angle increases, the LOS of the antenna rotates until the antenna is pointing directly upward at which time the elevation angle is 90 degrees.

<sup>19</sup> Edward E. Altshuler, Earth to Space Communication at M.M. Wavelengths (Cambridge, Mass: Air Force Cambridge Research Laboratory Report, AFCRL-65-566, Aug., 1965).

Table I  
RF Loss for Various Atmospheric Conditions and Antenna Elevation Angles  
Spillover Loss = 10°K; Frequency = 15 GHz

Elevation Angle (degrees)	Sky Conditions	Antenna Noise (°K)	Loss (db)
90	clear sky	14	0.08
	rain @ 1mm/hr	-	-
	rain @ 10mm/hr	-	-
60	clear sky	16	0.1
	rain @ 1mm/hr	-	-
	rain @ 10mm/hr	-	-
45	clear sky	20	0.14
	rain @ 1mm/hr	60	0.85
	rain @ 10mm/hr	165	3.5
30	clear sky	23	0.2
	rain @ 1mm/hr	80	1.25
	rain @ 10mm/hr	205	5.2
15	clear sky	38	0.48
	rain @ 1mm/hr	156	3.2
	rain @ 10mm/hr	268	13.5

millimeter per hour occurs about 3.4 percent of the time and that rain heavier than 10 millimeters per hour occurs less than 0.16 percent of the time. Thus, the probability of a rain capable of putting the system completely out of commission is less than the desired availability value. Even with the heavy rain, the possibility of using the TDRS antenna in the region above fifteen degrees elevation exists without resorting to diversity techniques to increase the probability of uninterrupted operation.

System Noise Temperature Considerations: The noise temperature of the pre-amplifier is a critical system parameter and is closely related to the overall performance of the system. Thus, a survey of the type of preamplifier devices that are available and will be available in the millimeter range (particularly at 16 GHz) for launch in the 1976-1980 time frame will be very useful to the trade-off analysis.

Several types of devices are worth mentioning for future applications. These are the following:

- (1) Tunnel Diode Amplifier (TDA)
- (2) Traveling Wave Tube Amplifier (TWTA)
- (3) Parametric Amplifier (Paramp) cooled and uncooled
- (4) Traveling Wave Maser Amplifier (Maser), cooled.

The TDA shows little noise-figure (NF) deterioration as frequency increases from 100 MHz to 20 GHz. However, NF performance has not improved significantly in the past three years.<sup>20</sup> Typically, the TDA is a broadband device with percent bandwidth ranging from 3.5 to 18. The TDA has a NF between three and seven db or a receiver noise temperature between 290°K and 1160°K. Rapid developments are being made in the design of the hybrid-integrated-circuit tunnel diode amplifiers; however, the NF is still too high (1.0 to 0.5 db required) for the TDRS application.

The TWTA is a large bandwidth device. The TWTA's main attributes are its large dynamic range, extremely large bandwidth, high gain and power output. The basic fault with the TWTA is its NF. Typically, the TWTA has a NF which ranges between seven and eleven db, or a receiver noise temperature between 1160°K and 3350°K, in the seven to 18 GHz frequency region.<sup>21</sup>

The paramps both cooled and uncooled are gaining importance as their reliability, long-term stability, and NF continue to improve. With successive refinements in varactor fabrication and low-loss, four-port circulators, the uncooled paramp is virtually

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<sup>20</sup>N. E. Feldman, "Syllabus on Low-Noise Microwave Devices," The Microwave Journal, July, 1969, p. 60.

<sup>21</sup>Ibid, p. 62.

unchallenged in the 80-200°K noise temperature range.<sup>22</sup> The present estimated operating life for the uncooled paramp is 5000 hours and for the cooled paramp the operating life is 2000 hours.<sup>23</sup> As varactors with cut-off frequencies up to 700-900 GHz become available, the noise temperature of the paramp will approach the theoretical level of zero. The paramp is a broadband device; presently, uncooled paramps are available with 500 MHz bandwidth. Cooling paramps can lower their noise temperature to 20°K; this can be translated to a receiver which has a NF of approximately 0.25 db. Actually the cooled paramp has no intrinsic operating temperature or intrinsic pump frequency. Paramps need not be cooled by liquid helium but can operate at any stabilized temperature, thus simplifying the refrigerator design. Rapid and simple tunability of the paramp makes it possible for it to operate in the cooled and uncooled state; thus, the paramp offers a degree of availability that other devices cannot duplicate. The low NF, broadband capability and other favorable features makes the paramp a strong choice for the front-end design.

The maser provides the current extreme in low-noise performance. The noise temperature of a maser is typically four to eight °K. Furthermore, masers have a large dynamic range and can operate at high frequencies 40-60 GHz. The average mean time between failures (MTBF) ranges from 1000 to 13,000 hours. A calculated MTBF of two years with a 99 percent confidence level has been established.<sup>24</sup> The major drawback with the maser amplifier is its narrow bandwidth, when compared to a paramp. Typically, the maser is capable of achieving 150-200 MHz bandwidth. Another undesirable feature of the maser amplifier is that it must be cooled; consequently, if the cryogenic refrigeration fails, the maser becomes inoperative.

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<sup>22</sup>C. Louis Cuccia, Todd G. Williams, Phil R. Cobb, Allen E. Small, James P. Rahilly, "RF Design of Communication-Satellite Earth Stations, Part 2," Microwaves, June, 1967, p. 31.

<sup>23</sup>Ibid, p. 32.

<sup>24</sup>N. E. Feldman, "Syllabus on Low-Noise Microwave Devices," The Microwave Journal July, 1969, p. 65.

In summary, it appears that the cooled paramp offers the best choice of achieving the 2 GHz bandwidth at a NF of 1.0 to 0.5 db; this corresponds to a receiver noise temperature of 75°K to 36°K, respectively.

It should be noted from Table I, that the minimum system temperature exists when the antenna has an elevation angle close to 90 degrees. However, at the GSFC site the elevation angle will range between 15 and 50 degrees. Operating the antenna at elevation angles less than 15 degrees increases the system noise temperature considerably.

If the operation of the antenna system is required for elevation angles less than 30 degrees, the noise contributed by the troposphere is the dominating influence and the low-noise receiver contributes a negligible amount to the total system noise temperature (see equation A.3 in Appendix A).

Gain Limitations of Reflector Antennas: The generally accepted formula for relating gain to frequency and surface tolerance was suggested by J. Ruze.<sup>25, 26</sup>

$$G = \eta \left( \frac{\pi D}{\lambda} \right)^2 e^{-\left( \frac{4\pi\sigma}{\lambda} \right)^2} \quad (4)$$

where

D is diameter of antenna in feet,

$\lambda$  is the operational wavelength in feet

$\sigma$  is the rms deviation of the antenna surface in feet

$\eta$  is aperture efficiency includes effect of spillover, aperture blockage, front-end losses and nonuniform illumination.

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<sup>25</sup> John Ruze, "The Effect of Aperture Errors on the Antenna Radiation Pattern," Suppl. al Nuevo Cimento, Vol. 9, No. 3, 1952, pp. 364-380.

<sup>26</sup> John Ruze, "Antenna Tolerance Theory-A Review" Proceedings of the IEEE, April, 1966, p. 635.



The above expression contains two factors: the first term is the normal gain formula for a perfect reflector and the second term is an exponential factor which relates the effect deviations from a perfect paraboloid have on the gain of the antenna.

As expected, for a given tolerance and diameter the antenna gain increases as frequency of operation increases. However, a point is reached at which the exponential factor dominates, and a further increase in frequency results in a decrease of the gain. This point at which the gain is a maximum for a given reflector (when  $\lambda = 4\pi\sigma$ ) is called the gain-limit point; and the loss at this point due to surface tolerance effects is 4.3 db.<sup>27</sup>

The same phenomenon can be observed if the operating frequency is fixed and the diameter is varied. As the reflector size increases the deviations on the edge of the dish become larger and, consequently, the total rms deviations become larger. After a given size, the gain begins to drop off from the gain-limit point, i.e.,  $4\pi\sigma > \lambda$ .

The TDRS ground station gain requirements are established by the TDRS-to-ground station link analysis. Table II shows the results of the TDRS-to-ground link calculations for receivers having NF's of 1.0 db and 0.5 db. In the link calculations, the diameters are derived for two values of  $\sigma$  ( $\sigma = 0$  and  $\sigma = 0.040$  inches). Thus, it can be seen from Table II that if an antenna is built with a surface tolerance of 0.040 inches, the size of the antenna can not be less than 100 feet for the receiver having a NF of 1.0 db and the size of the antenna can not be less than 85 feet for the receiver having a NF of 0.5 db.

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<sup>27</sup>Ibid, p. 635.

Table II

## Results of TDRS-to-Ground Link Calculations

Frequency = 16 GHz

Receiver Bandwidth = 2 GHz

	Preamp NF = 1.0 db	Preamp NF = 0.5 db
Transmitted Power 20 watts	+ 43.0 dbm	+ 43.0 dbm
Transmitted Gain 4 foot antenna, $\eta = .55$	+ 43.5 db	+ 43.5 db
Spacecraft Losses	- 2.0 db	- 2.0 db
Equivalent Isotropic Radiated Power (EIRP)	+ 84.5 dbm	+ 84.5 dbm
Space Loss	-208.8 db	-208.8 db
Atmospheric Attenuation (clear sky at 30° ele- vation)	- 0.2 db	- 0.2 db
Feed loss ( $\alpha = 0.89$ )	- 0.5 db	- 0.5 db
Noise Power ( $T_s = 127^\circ\text{K}$ for NF = 1.0 db)	- 85.6 dbm	-
Noise Power ( $T_s = 88^\circ\text{K}$ for NF = 0.5 db)	-	- 87.1 dbm
Carrier-to-Noise Ratio (CNR)	- 39.4 db	- 37.9 db
Required CNR	+ 30.0 db	+ 30.0 db
Gain Margin	0.6 db	0.6 db
Required Gain of TDRS Ground Antenna	70.0 db	68.5 db
Ground Antenna Diameter for $\eta = 0.6$ and for $\sigma = 0$ ,	80 feet	68 feet
and $\sigma = 0.0$ 40 inches	100 feet	85 feet

Recently, Jet Propulsion Laboratory (JPL) performed a study on ground antenna systems for deep-space communications applications. In the study, a functional relationship between surface tolerance and the antenna diameter was presented.<sup>28</sup> The data on the rms surface tolerance represented the total deviations from the true paraboloid and represented the surface accuracy under normal operating conditions. Thus, the mathematical expression included all factors combined. These factors included manufacturing inaccuracies as well as surface deflections caused by environmental loads such as wind, gravity and thermal effects. The functional expression is given by the following:

$$\sigma = \gamma D \quad (5)$$

where

$\sigma$  is the rms surface tolerance in feet,

$\gamma$  is the proportionality constant for various  $\sigma/D$  ratios; it varies from 0.25 to  $1.0 \times 10^{-4}$ , and

$D$  is the diameter of the antenna in feet.

Figure 6 shows the gain-limit point of antennas for various values of  $\gamma$  as defined in equation (5).

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<sup>28</sup>Phillip D. Potter, William D. Merrick, and Arthur C. Ludwig, "Big Antenna Systems for Deep-Space Communications," Astronautics and Aeronautics, October, 1966, pp. 86, 87.

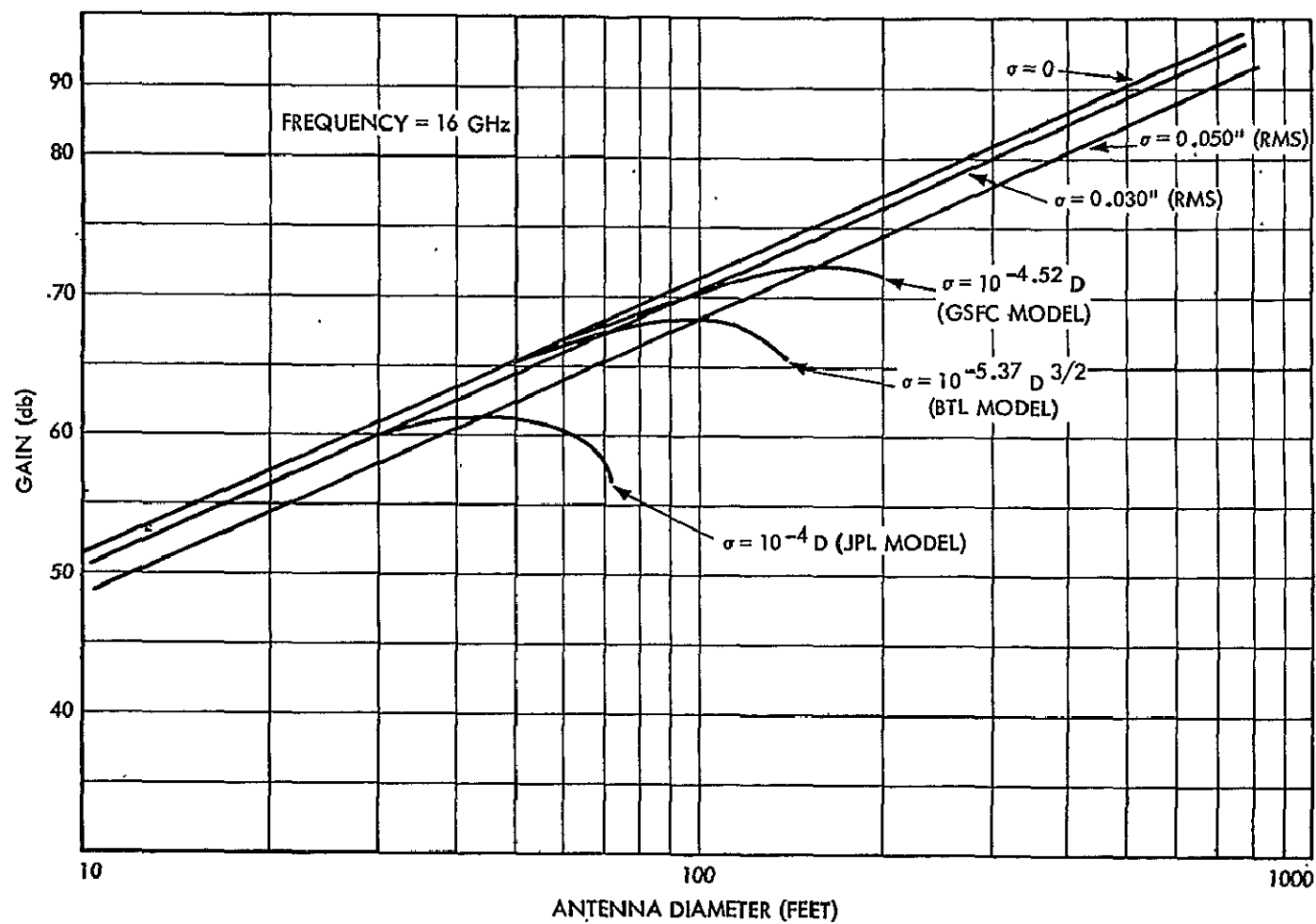


Figure 6. Gain-Limit Antennas As Function of Surface Tolerance (Sigma)

### 3.2 Radome Considerations

The large single antenna operating at  $K_u$ -band is susceptible to a variety of adverse environmental conditions; consequently, the use of a radome should be seriously considered. The advantage of the radome is that it protects the antenna from the effects of the common elemental conditions such as solar heat, wind, snow, ice, rain and dust. Specifically, these conditions can seriously affect the antenna in the following manner:

(1) Direct solar heat can disturb the antenna reflecting surface contour accuracy and differential solar thermal distortion can degrade the antenna's beam pointing accuracy.

(2) The influences of wind can be even more serious than the solar heat effect. An antenna structure and high-gain antenna servo drive and control subsystem can become unstable under buffeting winds as low as 30 miles per hour. Excitation or distortion under high wind loading can jeopardize its tracking performance also.

(3) Accumulations of ice, snow and possibly rain, if suitable drainage is not provided, can interfere with antenna performance. Radomes also retard physical deterioration, reduce maintenance requirements, and increase equipment reliability.

With a radome, load-carrying structural members can be connected more directly than on an exposed antenna thereby increasing the rigidity-to-weight ratio. Thus, the structure's natural resonant frequency can be increased by possibly 10 percent and the weight reduced by 15 to 20 percent.<sup>29</sup>

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<sup>29</sup>J. C. Dolling, R. W. Blackmore, W. J. Kinderman and K. B. Woodard, "The Mechanical Design of the Horn-Reflector Antenna and Radome," The Bell System Technical Journal, July 1963, p. 1143.

The effects of a radome on the electromagnetic properties of the antenna are: (1) a loss due to energy absorption by the dielectric and (2) an increase in system noise temperature due to energy scattering. Table III is a compilation of calculations made on gain losses and noise temperature increases for various climatic conditions. For a detailed discussion see Appendix A.

Table III  
Results of Calculations Showing Effects of Radome  
on Gain and Noise Temperature

Weather Conditions at 30° Elevation	Loss in Antenna Gain (db)	Radome Noise Temperature (°K)
clear sky	1.05	negligible
light rainfall 0.25 mm/hr	1.75	37
moderate rainfall 2.54 mm/hr	3.75	81
heavy rainfall 25.4 mm/hr	13.65	120

### 3.3 The Effectiveness Criterion for the TDRS Ground Station

In Section 3.1, factors related to system availability were studied. Two basic variables were involved in the study: equipment reliability and weather conditions. It was noted that the MTBF of the equipment and the amount of rainfall basically characterizes the system performance. System characteristics such as pointing angle of the antenna and duty cycle are also important and relate very closely to the other two characteristics;

Considerable attention was paid to the system noise temperature. The amount of literature on this subject is extremely large. The degree of interest reflects the importance being given by designers to the problem of noise temperature reduction. It was noted that the receiver front-end (preamplifier) is a significant contributor to the system noise temperature; however, when the preamplifier is cooled down sufficiently its noise contribution becomes a minor factor. It was noted that sky noise is a function of the antenna pointing angle, the weather conditions and the operating frequency. Basically, antenna effectiveness is inversely related to system noise temperature.

The parametric study on gain-limitations brought to light the crucial factors of surface tolerance, gain and the dish diameter. Using Ruze's formula, equation (4), one can obtain the gain-limit point; it is the maximum gain that can be achieved for a given frequency and tolerance. The maximum gain can be mathematically stated as follows:

$$G_{\max} \approx \frac{\eta}{43} \left( \frac{D^2}{\sigma^2} \right). \quad (\text{see reference 9, p.636})$$

In section 3.2, the two basic configurations were studied to determine the all-essential characteristics of the antenna system and to determine the model of an array which may be analyzed on a comparative basis with the single dish concept.

One other aspect of system performance that should be considered is the command function. As previously mentioned, the command system should be capable of transmitting a stream of command bits to the TDRS at rates required to command and control the TDRS spacecraft as well as user satellites. It is anticipated that the frequency ratio between transmit and receive will not be very large; therefore, duplexing will require extreme care in the design to obtain adequate isolation between channels. Furthermore, the efficiency of the feed is adversely affected by the imposition of the

dual capability on the antenna system. Thus, to circumvent these problems, a separate command antenna system is assumed for the TDRS ground station. The size of the antenna will depend on the link requirements and, particularly, on the transmitting hardware available in the 1976-1980 time period that will operate efficiently and reliably at 16 GHz.

In Section 4.4, the command system costs are presented and the command system requirements are discussed. Thus, the assumptions required for determining the performance level of the antenna are consistent with the ones used in Section 4.4 and need not be discussed here.

From the discussion and analysis of the critical system parameters and the formulation of the basic antenna configurations to be studied, the following statement on the effectiveness of the desired TDRS ground station can be made:

For a given bandwidth (2 GHz);

for a given station availability (0.998);

for a given carrier-to-noise ratio (30 db);

for a given set of the following functional requirements:

- (a) capability of tracking one/two TDRS satellites,
- (b) capability of TDRS-user communication at any time, and
- (c) capability of commanding the TDRS; and,

for full compatibility with MSFN and STADAN networks, the TDRS ground station must achieve maximum antenna effectiveness. Antenna effectiveness is defined as the ratio of effective antenna gain to system noise temperature. Symbolically,

$$AE = G/T_s \quad (6)$$



where,  $G$  is the effective antenna gain (antenna gain less line and feed losses) expressed in absolute units of gain or db; and  $T_s$  is the system noise temperature at the nominal antenna elevation angle of 30 degrees expressed in degrees Kelvin ( $^{\circ}\text{K}$ ) or db.

Table IV, shows the values of antenna effectiveness as a function of noise temperature changes due to changes in receiver noise figures and weather conditions.

Table IV

Antenna Effectiveness for Various Sky Conditions and Receiver Noise Figures

Antenna efficiency,  $\eta$ , = 0.6, Frequency = 16 GHz

Weather Conditions	Antenna Noise Temperature (°K)	Antenna Gain (G) <sup>2</sup>				System Noise <sup>1</sup> Temperature (T <sub>s</sub> )		Antenna Effectiveness (G/T <sub>s</sub> )			
		Receiver NF = 1.0 db		Receiver NF = 0.5 db				Receiver NF = 1.0 db		Receiver NF = 0.5 db	
		(Abs. Units) X10 <sup>6</sup>	(db)	(Abs. Units) X10 <sup>6</sup>	(db)	Receiver NF = 1.0 db (°K)	Receiver NF = 0.5 db (°K)	Receiver NF = 1.0 db (ABS × 10 <sup>3</sup> )	(db)	Receiver NF = 0.5 db (ABS × 10 <sup>3</sup> )	
Clear	23	10	70	7.1	68.5	127	88	78.7	48.9	80.6	49.1
rainfall 1mm/hr	80	10	70	7.1	68.5	187	148	53.5	47.3	48	46.8
rainfall 10mm/hr	205	10	70	7.1	68.5	313	274	32	45	26	44.2

Notes: 1.  $T_s = \alpha T_a + 290 (1 - \alpha) + 290 (NF - 1)$

where,

$\alpha$  = transmission coefficient = 0.89; it represents an RF line loss of 0.5 db.

$T_a$  = antenna noise temperature which includes two components,  $T_1 + T_2$ .  $T_1$  = antenna temperature mostly spillover and is taken to be  $10^{\circ}\text{K}$ ;  $T_2$  = sky noise temperature, related to the following formula:  $T_2 = 280 (1 - \alpha_1)$ ; the transmission coefficient,  $\alpha_1$  is a function of elevation angle and sky conditions.

2. The gains are calculated on the basis that a 30 db CNR will be available on a clear day at an elevation angle of 30 degrees.

## CHAPTER 4

### DEVELOPMENT OF COST MODELS

This chapter will consider the types of costs involved in establishing a TDRS ground station and will analyze costs and establish cost models associated with the various configurations chosen for study.

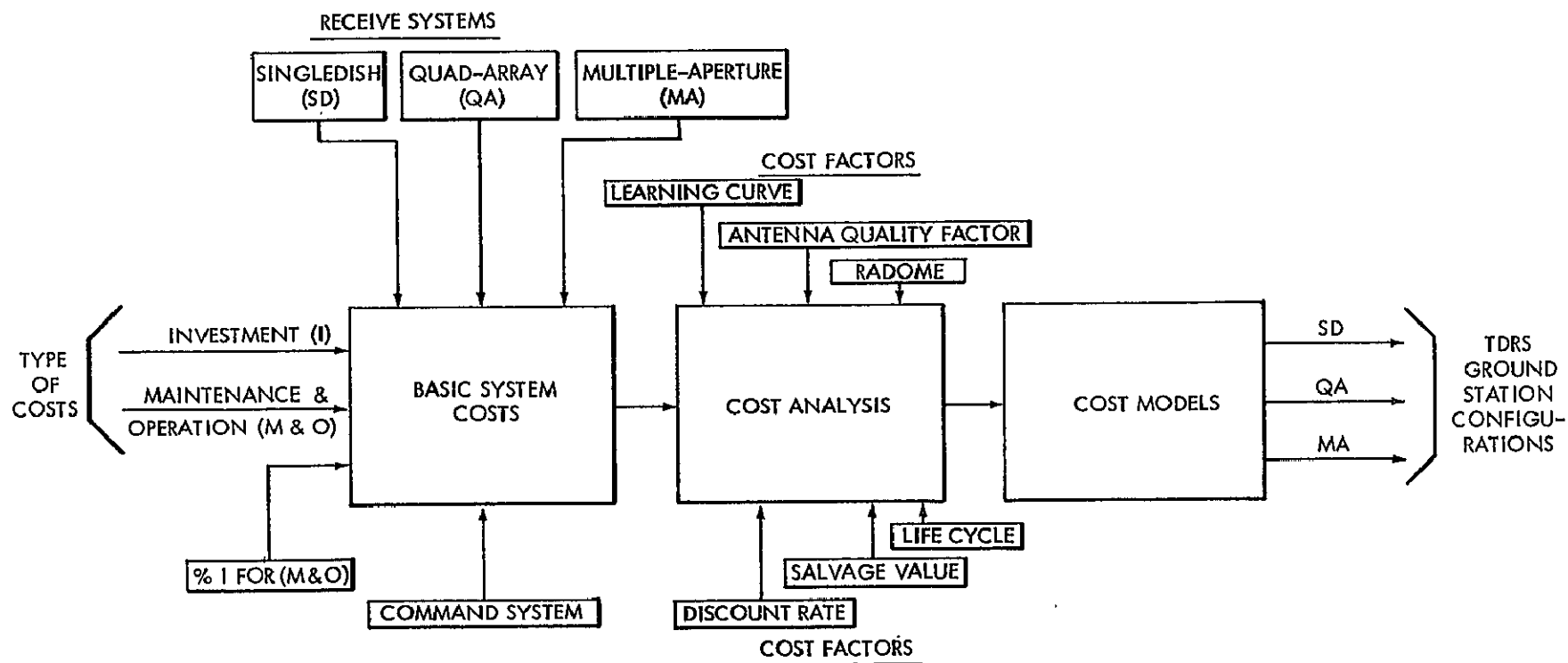
Figure 7 is a flow graph illustrating the various interelement relationships involved in the development of cost models. The procedure can be described as follows:

- (1) Establish basic system concept and consider various alternatives,
- (2) Determine types of system costs; e.g. investment and annual operating costs,
- (3) Develop a list of crucial cost factors to be used in analyzing system costs; and
- (4) Construct cost models for various ground station configurations in light of key limiting assumptions.

#### 4.1 Types of System Costs

Basically, there are two types of costs considered in the analysis; these are: investment costs, i.e. costs related to purchase of the antenna system including the basic electronic package consisting of a preamplifier for the sum channel and a tracking receiver, and maintenance and operation costs, i.e. costs related to maintenance and operating personnel and equipment replacement.

Investment Costs: The cost elements in the antenna system are: (a) reflector, (b) base or pedestal, (c) feed, (d) servo and drive system, (e) low-noise receiver, (f) tracking receiver, and (g) erection and checkout of antenna system. The analysis will



I = ANTENNA + ELECTRONICS EQUIPMENT COSTS

M & O = PERSONNEL & EQUIPMENT REPLACEMENT COSTS

Figure 7. Flow Graph for the Development of the TDRS

Ground Station Cost Models

be confined to the study of the above mentioned cost elements. Other cost elements related to the TDRS ground station installation which will not be considered because they remain relatively fixed regardless of the ground station configuration are: (a) site preparation, (b) building construction, (c) power plant, and (d) survey and land acquisition. These costs will be treated as sunk or irrelevant costs for the purposes of this analysis.

Annual Operating Costs: Costs associated with the operation and maintenance of the equipment procured and placed into operations are defined as annual operating costs (AOC). A recent GSFC study<sup>30</sup> had established the annual direct and indirect cost of operations for a typical network tracking station at approximately 20 percent of the investment costs; also, the annual equipment costs were set at 10 percent of the investment costs. The equipment costs generally include all station equipment costs; however, for the purposes of this analysis only the cost elements related to the pertinent electronic equipment will be considered. Mathematically, the AOC can be represented as follows:

$$AOC = 0.2I + 0.1I_1 \quad (7)$$

where,

I is total investment as described above, and

$I_1$  is that part of the total investment which is related to the preamplifier(s) tracking receiver(s), and other appropriate electronic equipment.

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<sup>30</sup>Werner Gruhl, Paul Villone and William A. Mecca, Jr., Tracking and Data Relay Satellite Network (TDRSN) Cost and Benefit Study, (Greenbelt, Md., GSFC X-264-69-526, Dec. 1969), p. 9.

Note that the equivalent annual cost (EAC) includes the discounted rate of the total investment and AOC for the assumed write-off period. The discussion related to EAC is deferred to Chapter 5.

## 4.2 Cost Analysis Procedure

As previously mentioned, the procedure will include a discussion of the crucial cost factors and then taking them into account in analyzing the costs. The pertinent cost factors are the following:

(1) Learning curve. When more than one-of-a-kind system is purchased, it is generally assumed that costs will decrease as a function of the learning process. Consequently, learning curves have been widely used in negotiating contract prices and estimating costs of multiple systems.<sup>31</sup> Studies performed by JPL on large dish systems assumed a 95 percent learning curve.<sup>32</sup> The JPL assumption will be used in this analysis as well. The 0.95 learning curve factor assumes that the cost of the antenna system is reduced by 5 percent each time the order is doubled. Thus, for a quantity of two the cost per unit is 0.95 of original cost and for a quantity of four the cost per unit is 0.9025 of original cost. Figure 8 is the learning curve related to the TDRS ground station cost analysis.

(2) Antenna Quality Factor. This factor is related to the surface tolerance parameter and is defined in equations (12.1) and (12.2). Essentially, it is a penalty (reward) for deviation from the standard cost curve. The curve is derived in the forthcoming section on station models.

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<sup>31</sup>Robert N. Anthony, Management Accounting: Text and Cases (3rd Ed; Homewood, Illinois: Richard D. Irwin, Inc., 1964), p. 608.

<sup>32</sup>Phillip D. Potter, William D. Merrick, Arthur C. Ludwig, Large Antenna Apertures and Arrays for Deep Space Communications (Pasadena, Calif.: Jet Propulsion Laboratory Report No. 32-848, Nov. 1, 1965), p. 14.

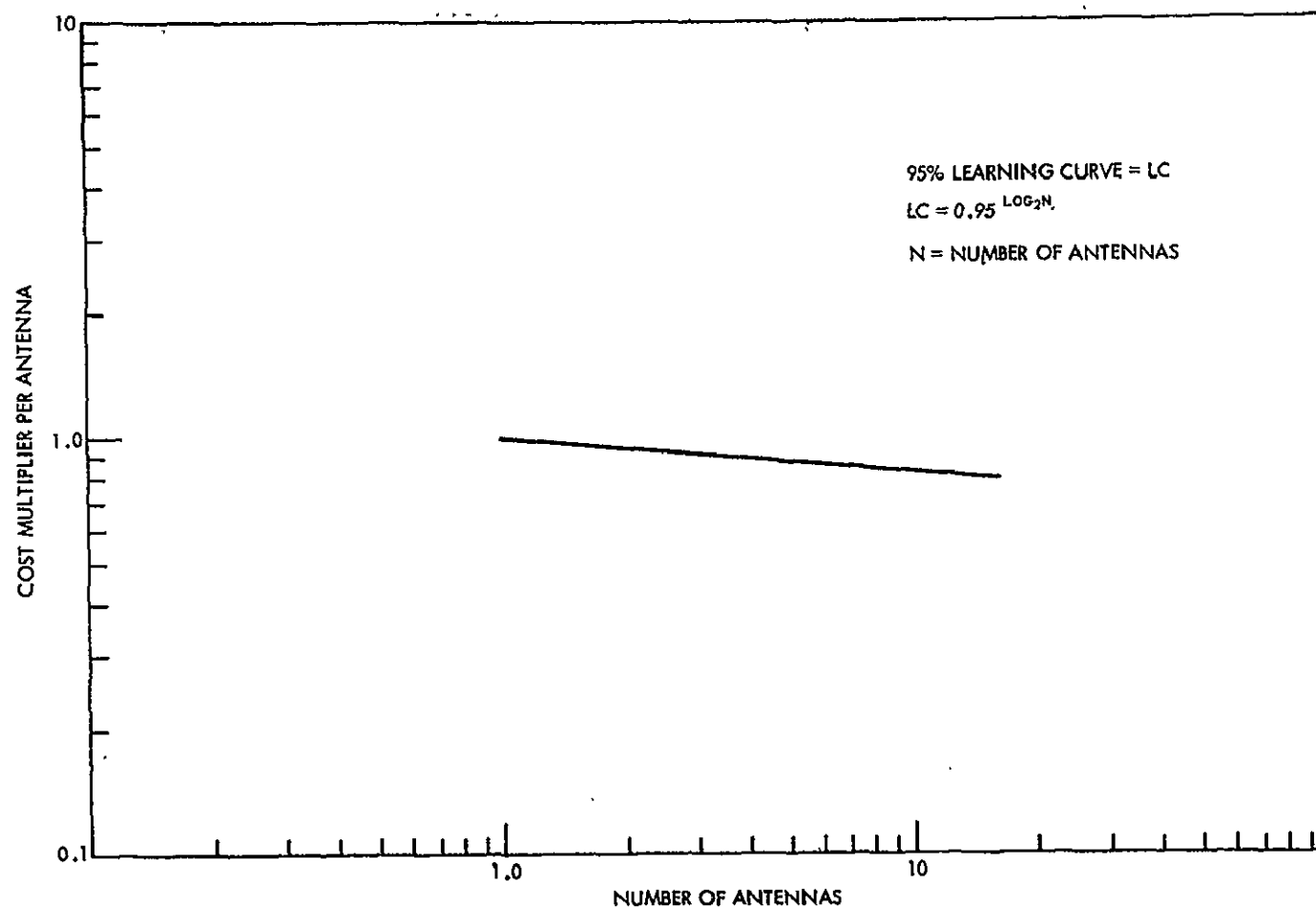


Figure 8. Learning Curve (LC) for TDRS Ground Station Study

(3) Life-Cycle of the Antenna System. To determine the proper rate of return and the break-even point for the investment, a life cycle of the system must be estimated. There are at least two ways to establish the "time horizon" (life of the equipment); these are: (a) the physical life, and (b) the technological life. For the cost-benefit analysis presented in Chapter 5, the life cycle of the TDRS ground station is keyed to the physical life of the antenna system which is assumed to be 15 years.

(4) Discount Rate. The Bureau of Budget developed guidelines for evaluating the rate of return on government investments. The acceptable rate of return for government projects as established by the Water Resources Council, was related to the current yield on Government bonds.<sup>33</sup> The discount rate for fiscal years beyond 1970 was set at 10 percent. In the analysis presented in Chapter 5, a 10 percent discount rate will be used.

(5) Salvage Value. Recent GSFC study,<sup>34</sup> indicates that the amount of reusable antenna equipment at the end of a technological life cycle can vary from a pessimistic 58 percent to an optimistic 82 percent. Since this study assumes a life cycle based on the physical life of the system, the salvage value is assumed to be zero. The reason for this assumption stems from the fact that specialized equipment, such as that which is related to the antenna system, is usually fully scrapped in governmental projects.

(6) Radome. Since control of the environment may be necessary, the cost of a radome must be given serious consideration in the cost analysis. Consequently, the cost model for the SD system will also include the cost of the radome.

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<sup>33</sup>Robert P. Mayo, Discount Rates and Procedures to be Used in Evaluating Deferred Costs and Benefits (Bureau of the Budget Circular No. A-94, June 26, 1969), p. 3.

<sup>34</sup>John E. Moyle, Eula B. Paseur, and Philip B. Pease, Cost Effectiveness Analysis of Telemetry Data Acquisition by the Space Tracking and Data Acquisition Network (STADAN) (Greenbelt, Md.: GSFC X-520-69-275, July 1969), p. 13.

### 4.3 Antenna Cost Models

The development of antenna cost models has been an inexact science for many years. The reasons for the inexactitude are manifold; however, the gist of the problem lies in the fact that large inconsistencies exist on basic assumptions and on the fact that cost centers have been misplaced or misinterpreted.

In researching the subject, the author found that the most widely accepted cost model relates the antenna size to cost in a power law relationship, viz;

$$\text{Cost} = n D^b \quad (8)$$

where, D is the antenna diameter in feet, and n and b are constants.

The formula was first applied by JPL in studies related to large dishes.<sup>35</sup> Subsequently, the model was refined to take into account maintenance and operation (M & O) costs and electronics costs for the array case.

In developing antenna cost models for the trade-off study of the TDRS ground station, the following models were considered:

(1) Single dish model which includes costs for the feed, reflector, pedestal and servo electronics. Models will be developed for an exposed antenna and for an enclosed antenna (with radome).

(2) Quad-array model which includes all of the costs in model (1) except the consideration of radome costs. The radome case is not considered because it is assumed that availability of the system will be increased sufficiently by the signal combining

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<sup>35</sup> Phillip D. Potter, William D. Merrick, Arthur C. Ludwig, Large Antenna Apertures and Arrays for Deep Space Communications Pasadena, Calif: Jet Propulsion Laboratory Technical Report No. 32-848, November 1, 1965), p. 15.



process to enable the system to operate at an acceptable level even under adverse weather conditions.

(3) Multiple-aperture model which includes all of the costs related to model (1) without the radome.

The TDRS ground station models (1), (2) and (3) will be adjusted to include the cost(s) of the front end(s), the tracking receiver(s); and the cost of the typical command system.

Single Dish Model: Recently, Bell Telephone Laboratories (BTL) under a GSFC contract, developed a realistic cost model.<sup>36</sup> The BTL model modifies the one described in equation (8) and is given as follows:

$$\$_0 = a_1 D^{-1/3} e^{D/45} \quad (9)$$

where,

$\$_0$  = costs of exposed antenna; it includes structure, drives and control,

D = diameter of dish in feet,

e = base number 2.718, and

$a_1$  = proportionality constant  $6.70 \times 10^5$ .

Equation (9) was obtained by fitting three basic antenna systems; all were built by a single company and good rms surface tolerance information was available for all three antenna systems. Figure 9 shows the cost curve plotted as a function of the three basic antenna diameters. It should be noted that when other existing antennas are plotted on the graph, there is good correlation for antennas ranging in diameters

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<sup>36</sup>J. S. Cook, Project manager, Deep Space Communication and Navigation Study (Final Report, Prepared by Bell Telephone Laboratories for NASA, Goddard Space Flight Center, Vol. 2, May 1, 1968), p. 40.

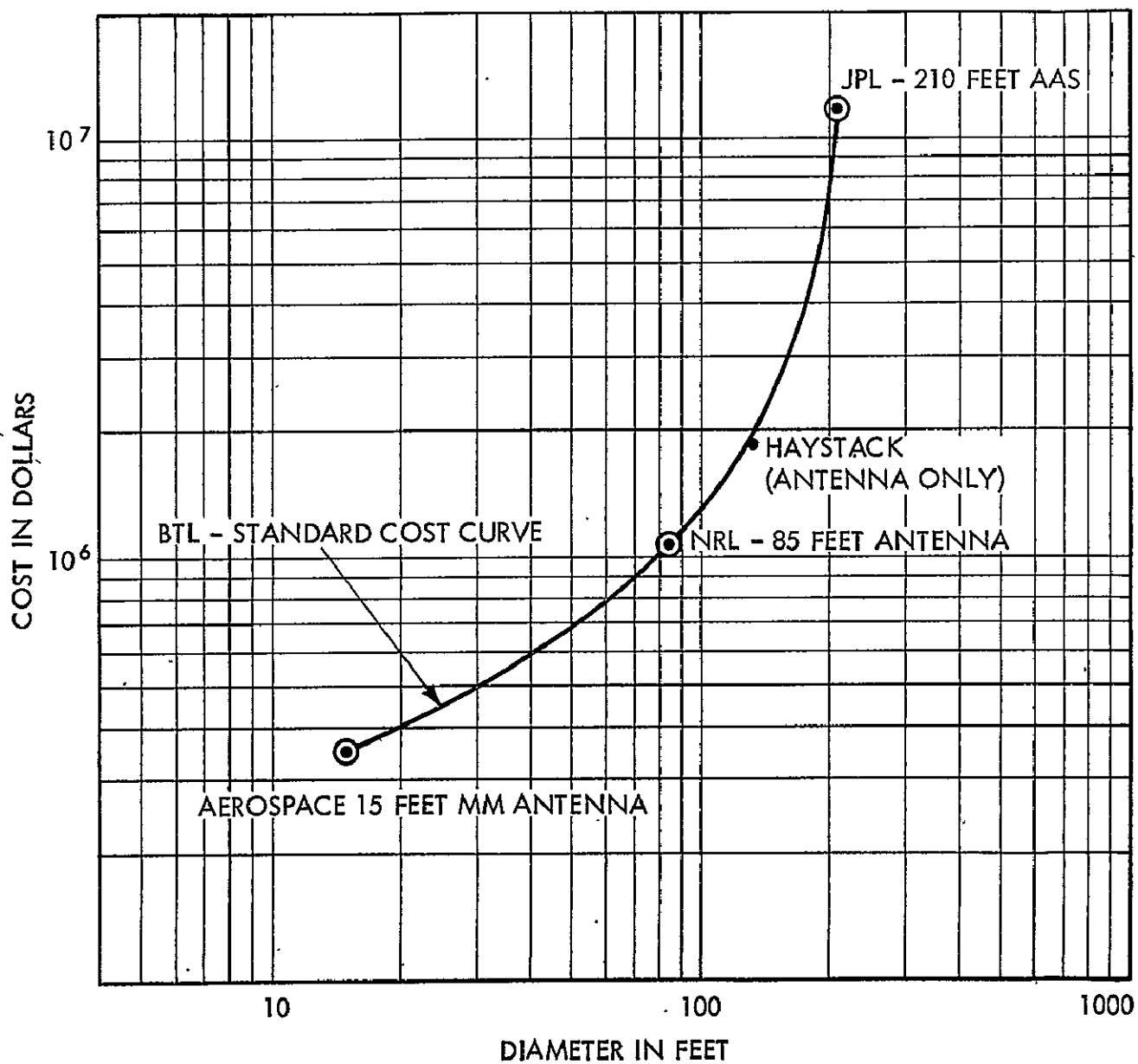


Figure 9. Cost Versus Diameter for Basic Antenna Structures

from 15 feet to 120 feet. The authors recommend the use of the equation over a diameter range of 10 to 250 feet.<sup>37</sup>

The BTL study also developed the cost-diameter relation for antennas with a radome. The relation is satisfactory for antennas which range in diameter from 20 to 500 feet. This relation is as follows:

$$\text{\$R} = a_2 D^{1.3} \quad (10)$$

where,

\text{\\$R} = Costs of antenna with radome; it includes structure, radome, drives and control,

$a_2$  = proportionality constant  $6.75 \times 10^3$

D = diameter of dish in feet.

In considering the standard cost curve as shown in Figure 10, the BTL study took into account the rms surface tolerance factor. The functional relationship is of the following form:

$$\sigma = C_1 D^{3/2} \quad (11)$$

where,  $\sigma$  is the rms surface tolerance in millimeters

D is reflector diameter in feet, and

$C_1$  is constant of proportionality and has two values:

$C_1 = 1.3 \times 10^{-3}$  for exposed antennas

$C_2 = 4.6 \times 10^{-4}$  for antennas under a radome.

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<sup>37</sup>Ibid, p. 40.

It should be noted that the JPL study, referred to in Section 3.1 under gain-limitations of reflector antennas, assumed the expression relating surface tolerance to diameter as a linear function (see equation (5)). The gain limit curves for various proportionality constants were plotted in Figure 6. It should be noted also that the proportionality constant relating the surface tolerance to antenna diameter for the GSFC model is linear and has a higher value than the one associated with the BTL model.

The choice of the linear function for the GSFC model is motivated primarily by the Ruze argument that antenna gain-limit point is proportional to the square of the precision of manufacture  $(D/\sigma)$ .<sup>38</sup> Thus, for the given frequency and gain the surface tolerance is directly proportional to the diameter. The choice of the  $\gamma$ -value for the GSFC model is based on a survey of all large antenna manufacturers conducted by B. R. Stack which produced a consensus that a "shop practice" rms surface tolerance for antennas ranging in diameters from 85 to 100 feet is approximately 0.04 inches.<sup>39</sup>

Since the GSFC model considers a higher quality antenna than the BTL model, an adjustment in the cost function is required. To deal with the effects of moving off the standard (BTL) costs, a quality factor is introduced into the cost equation (9). The quality factor relates an incremental change in rms surface tolerance,  $\Delta\sigma$ , to an incremental change in cost,  $\Delta\$$ . The approach was first introduced by Stack.<sup>40</sup> The actual rms,  $\sigma_A$ , and the actual cost  $\$A$  are expressed as:

$$\sigma_A = F_1 \sigma = \frac{\sigma}{x} \quad (12.1)$$

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<sup>38</sup> John Ruze, "Antenna Tolerance Theory -A Review" Proceeding of the IEEE, April, 1966, p. 636.

<sup>39</sup> B. R. Stack, An Approximate Expression for the Cost-Gain Relationship in large Parabolic Antennas (Menlo Park, Calif.; Stanford Research Institute, December, 1967), p. 7.

<sup>40</sup> Ibid, p. 12.

$$\sigma_A = F_2 \sigma_0 = e^{(x-1)} \sigma_0 \quad (12.2)$$

where

$\sigma_A$  = actual rms surface tolerance,

$F_1 = 1/x$  a quality factor; the range of  $x$  is  $0 < x < \infty$ . For  $x > 1$  the rms surface tolerance is less than the standard surface tolerance and for  $x < 1$  the rms error is larger than standard surface tolerance

$F_2 = e^{(x-1)}$  quality factor on cost corresponding to change in  $\sigma$  to  $\sigma_A$ ,

$\sigma$ ,  $\sigma_0$  were defined previously.

It should be noted that the possible reduction in cost is limited to one-third of the standard cost regardless of increase in surface tolerance.<sup>41</sup> Combining equation (9) with (12.2) and equation (11) with (12.1) and recalling equation (4) to be the gain relation of the gain-limited antenna, the following equations can be established by direct substitution:

A. For exposed antennas:

$$\sigma_A = \frac{C_1 D^{3/2}}{x} \quad (13.1)$$

$$\sigma_A = a_1 D^{-1/3} e^{(a_3 D + x - 1)} \quad (13.2)$$

$$G = \eta (a_4 D f)^2 e^{-(a_5 \sigma f)^2} \quad (13.3)$$

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<sup>41</sup>J. S. Cook, Deep Space Communication and Navigation Study (Final Report prepared by Bell Telephone Laboratories for NASA, GSFC Vol. 2, May 1, 1969), p. 44.

where,

$\sigma$  is the rms surface tolerance in millimeters

D is antenna diameter in feet

G is gain in db

$\$A$  is actual cost in dollars

$\eta$  is aperture efficiency, taken as 0.6 for this study

f is frequency in GHz

x is nondimensional quality factor. The constants have the following values:

$$C_1 = 1.3 \times 10^{-3}$$

$$a_1 = 6.7 \times 10^5$$

$$a_3 = 2.22 \times 10^{-2}$$

$$a_4 = 3.20$$

$$a_5 = 4.19 \times 10^{-2}$$

B. For enclosed antennas:

$$\sigma_{AR} = \frac{B_1 D^{3/2}}{x} \quad (14.1)$$

$$\$_{AR} = e^{(x-1)} [a_2 D^{1.3} - B_3 D^{1.85}] + B_3 D^{1.85} \quad (14.2)$$

$$G_{AR} = \frac{\eta}{L} (B_4 D f)^2 e^{-(B_5 \sigma f)^2} \quad (14.3)$$

It should be noted that for the radome case the cost factor was only applied to the antenna since the cost of the radome is independent of the quality of antenna inside.

However, the total cost of the antenna includes the radome costs,  $B_3 D^{1.85}$ . The factor

L is the attenuation loss due to the presence of the radome. It is assumed that the radome loss is 1.0 db, see Table III. The constants related to the equations (14.1), (14.2) and (14.3) have the following values:

$$B_1 = 4.6 \times 10^{-4}$$

$$a_2 = 6.75 \times 10^3$$

$$B_3 = 1.28 \times 10^2$$

$$B_4 = 3.20$$

$$B_5 = 4.19 \times 10^{-2}$$

$$L = 1.26 \text{ corresponding to } 1.0 \text{ db loss}$$

$$\eta = .65$$

The remaining cost element to be discussed as part of the TDRS ground antenna cost model is the cost associated with the basic electronic receiver package; viz., the preamplifier and the tracking receiver. Since the design of the tracking receiver poses no consequential technical difficulties, the discussion will center on the preamplifier design and the corresponding cost center related to the noise figure (NF).

Receiver Front-End Considerations: Since the system is to operate at 16 GHz, the sky noise is a significant contributor to the system noise temperature. Table I presented the values of antenna noise temperature as a function of the elevation angle. Within the range of antenna operation, 15 degrees elevation to 45 degrees elevation, the antenna noise temperature varies between 38°K to 20°K on a clear day and 156°K to 60°K on a moderately rainy day. Furthermore, a front-end receiver with a 1.0 db NF contributes a noise temperature of 75°K. Thus, in the region of operation, the receiver is a large contributor under the conditions of a transparent atmosphere. To reduce the

noise level of the receiver will require cooling and consequently, an increase in costs. The noise temperature of a preamplifier with a 0.5 db NF is 36°K. This receiver noise temperature, however, can be achieved with a gas helium cooling system; thus unlike the maser liquid cooling system, the cryogenic refrigerator for the paramp is less costly and requires less maintenance.

The cost of the front-end, as was noted, is a function of the desired receiver noise temperature. A range of system noise temperatures and associated receiver types and costs were derived in a previous study.<sup>42</sup> Table V is a compilation of the data presented in that study.

Multiple-Aperture Model: In surveying the field, it was found that several cost models have been developed for an array system. Two approaches that have been used are as follows:

(1) JPL Approach.<sup>43</sup> This scheme assumes that unit cost can be reduced by a learning curve factor of 0.95 each time the quantity is doubled; furthermore, the antenna cost model is of the form expressed in equation (8) where  $n = 4.37$  and  $b = 2.78$ . This approach also assumes no salvage value at the end of the write-off period. The array model can be expressed as follows:

$$C_A = N (0.95^{\log_2 N})^{4.37} D^{2.78} + C_M + (N - 1) 0.95^{\log_2 N} C_s \quad (15)$$

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<sup>42</sup>C. Louis Cuccia and Sheldon Teicher, "The Economics of Antenna Receiving Systems" (Microwaves, June, 1969), p. 90.

<sup>43</sup>Phillip D. Potter, et. al. Large Antenna Apertures and Arrays for Deep Space Communications (Pasadena, Calif.: Jet Propulsion Laboratory Technical Report No. 32-848, Nov. 1, 1965), p. 16.



Table V

## Receiver Noise Temperature and Costs Associated with Various Front End Designs

Type of Amplifier per channel	Range of Initial Costs (\$)		Range of Receiver Noise Temperature (°K)	Noise Figure (db)
Tunnel Diode Amplifier (TDA)	4,000 10,400		900 450	6.0 4.0
PARAMP (uncooled) (4)	(Excluding R&D) 12,000 26,000	(Includes R&D and Suppt. Equip.) 50,000 100,000	360 130	3.5 1.6
PARAMP (cooled to liquid nitrogen temp. 77°K)	(Excluding R&D costs) 27,200 (1) 50,000 (1)		115 75	1.45 1.0
PARAMP (cryogenically gas helium cooled to 17°K ambient)	(Excluding R&D costs) 60,000 (1) 125,000 (2)		30 17	0.43 0.25
MASER (liquid helium cooled to 4°K ambient)	Including all costs 200,000 250,000-500,000 (3)		8 5	0.15 0.01

- Notes: 1. Cost of the cryogenic refrigerator is about \$15,000 additional.  
 2. Cost of multiple stage cryogenic refrigerator between \$15,000 and \$20,000 additional.  
 3. Cost of closed-cycle refrigerator is at least \$80,000.  
 4. The uncooled PARAMP must be temperature stabilized.

where,

$C_A$  = station cost in dollars

$D$  = diameter of aperture element

$C_M$  = cost of master station electronics and facilities

$LC = 0.95^{\log_2 N}$  = learning curve factor, and

$C_s$  = cost of slave station electronics and facilities.

(2) BTL Approach.<sup>44</sup> The technique developed by BTL also assumes a learning curve factor of 0.95. The array cost model closely patterns the JPL array model. The essential difference between the two approaches is in the antenna model; the JPL antenna model is  $4.37 D^{2.78}$  and the BTL antenna model is  $6.7 \times 10^5 D^{-1/3} e^{D/45}$  where D is the diameter of aperture element.

The GSFC model will not agree completely with either of the two approaches mentioned. The reasons for the departure from the established approaches are the following:

- (1) The JPL master-slave concept is not a practical arrangement from the standpoint of TDRS ground station availability.
- (2) Since the TDRS ground station is to operate at  $K_u$ -band, the required surface tolerance may force the model to include a quality factor.

All in all, the BTL approach uses a more realistic cost model for the antenna system; consequently, a modified BTL model will be used in the cost sensitivity analysis procedure. Thus, the GSFC multiple-aperture (MA) cost model can be expressed, mathematically, as follows:

$$\$_{MA} = N (0.95^{\log_2 N}) [\$_A + \$_E] + \$_{TDU} \quad (16)$$

where,

$\$_A$  is defined in equation (13.2).

$\$_E$  is cost of the electronic package which includes the low-noise receiver and the tracking receivers (dual channel)

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<sup>44</sup>J. S. Cook, Deep Space Communication and Navigation Study (3 Vol. Whippany, N.J.: Bell Telephone Laboratory Report for NASA, GSFC, Vol. 3, May 1, 1968), p. 2-2.

$\$_{\text{TDU}}$  is cost of a time delay unit; and,

$(0.95^{10 \log_2 N})$  is the learning curve factor.

Quad-Array Model: Physically, the antenna consists of a cluster of reflectors which are mounted on a single pedestal to synthesize a single large aperture. Unfortunately, a literature search did not uncover the required information for developing a cost model. As Stack points out in his survey,<sup>45</sup> the overall cost of large antenna systems varies greatly with the technical requirements imposed on the system; furthermore, because of the proprietary nature of the cost breakdown of various cost elements, the determination of cost centers is extremely difficult using available published data. Fortunately, GSFC has been involved in the procurement and the installation of 30 foot, 40 foot and 85 foot antenna systems for almost a decade; consequently, in-house estimates can be made to develop a realistic quad-array (QA) cost model. It has been estimated that feed and reflector constitute about 40 percent of the total costs of an 85 foot antenna.<sup>46</sup> This estimate should be examined in light of other considerations. A cluster of four 45 foot reflectors, for example, would develop a performance which, is equal to a single 100 foot dish. The aperture area for the QA is 20 percent less, approximately; consequently, the servo drive requirements and the overall strength-to-rigidity ratio will be lowered, thereby reducing costs. However, offsetting costs related to the process of precisely placing and aligning the reflectors, designing and fabricating a special X-frame to minimize the phase front errors between reflectors, designing separate electronic cages, and developing a unique tie-back arrangement of the RF

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<sup>45</sup> B. R. Stack, An Approximate Expression for the Cost-Gain Relationship in Large Parabolic Antennas (Menlo Park, Calif.: Stanford Research Institute, December, 1967), p. 13, 14.

<sup>46</sup> Private communication with C. R. Grant, Stadan Engineering Division, GSFC on February 18, 1970.

cables through and from the structure into the control building will reduce the cost savings considerably. Consequently, the cost of the reflector-feed portion was taken at 35 percent of total antenna cost, less receivers, and the alidade structure and the base was taken at 65 per cent of the cost. The QA model can be expressed as follows:

$$\$_{QA} = N (0.95^{10 \log_2 N}) [0.35 \$_{A1} + \$_{F1}^*] + 0.65 \$_{A2} + \$_{TR}'' \quad (17)$$

where,

$\$_{A1}$  is the cost of the antenna with element reflector (equation 13.2),

$\$_{A2}$  is the cost of the antenna with equivalent aperture size (equation 9),

$\$_{F1}^*$  is the cost of front-ends, ( $\$_{F1}$  or  $\$_{F1}'$ ), and

$\$_{TR}''$  is the cost of other standard electronic equipment (tracking receiver).

Other terms have been previously defined.

Command System Model: The TDRS command system will be located at Goddard and will be configured to meet certain system requirements. From the command bandwidth requirements and the command transmitter power that will be available and for a known spacecraft receiver sensitivity, link calculations can be performed to determine the size of the command antenna. For this purpose, the following assumptions are made:

- (1) 1.0 KW of power is available for transmission,
- (2) Maximum command data bandwidth is 5 MHz wide,
- (3) spacecraft receiver NF is 12 db,
- (4) spacecraft antenna is 4 feet and is 55 percent efficient
- (5) transmission coefficient,  $\alpha = 0.6$ ; RF loss = 2.2 db.
- (6) required CNR is 30 db.

With the above assumptions the TDRS command system is determined in a straight forward fashion (see Appendix B). Table VI below summarizes the results of the link calculations and tabulates the costs associated with the installation. These costs

Table VI

## Estimated Cost of A Command System for TDRS Network

Antenna	Description	Cost (estimates)
Includes Structure, Feed, and Servo Electronics	6-foot reflector, feed, pedestal and drive mechanism	\$90,000
1 - 1.0 KW xmitter system	Power Amplifier, exciter, attenuator, filter, heat exchanger, primary power (MG set)	\$150,000-300,000 (includes development costs) est. avg. \$225,000
1 - Antenna and Xmitter Control Console	Servo, collimation and transmitter control panels, patch panels, meter and display units, protection circuits and verification systems	\$70,000
Command Encoder	TDRS - Command Encoder system and modulators	\$350,000 (includes R&D Costs)
	TOTAL COST PER COMMAND SYSTEM	\$735,000

will be an added fixed cost to station cost where it is appropriate. The cost estimates were obtained from several Goddard engineers knowledgeable in the design of the equipment specified.

Summary: It should be noted that the models developed did not take into account all the system costs. Factors related to M & O and consideration of the investment from the return standpoint must be included to complete the cost structures. Table VII is a summary of all the cost elements mentioned and relates them to total system cost models for the three configurations under study.

Table VII  
Summary of System Costs and the Development  
of Total System Cost Models

Cost Elements	Cost Models	Remarks
Basic Antenna System	$\$0 = a_1 D^{-1/3} e^{D/45}$	(Equation 9)
Quality Antenna	$\$A = \$0 e^{(X-1)}$	(Equation 12.2)
Radome	$\$R = a_2 D^{1.3}$	(Equation 10)
1. Receiver Front-End	$\$F_1^* = \$F_1$ or $\$F_1'$ where, $\$F_1 = \$65,000$	Noise Figure = 1.0 db related to $\$F_1$
2. Receiver Front-End	$\$F_1 = \$80,000$	Noise Figure = 0.5 db related to $\$F_1'$
1. Tracking Receiver	$\$TR = \$100,000$	Basic receiver incl. two channels
2. Tracking Receiver	$\$TR' = \$130,000$	Receiver to be used on SD & MA systems
3. Tracking Receiver	$\$TR'' = \$160,000$	Receiver to be used on QA system
Time Delay Unit	$\$TDU = \$225,000$	Unit to be used on MA system
Command System	$\$C = \$C_1 + \$C_2 = \$735,000$ $\$C_1 = \$225,000$ $\$C_2 = \$510,000$	A 1.0 KW system Transmitter Command Encoder & Antenna system
1. AOC for SD	$\$MO = 0.2 (\$A + \$F_1^* + \$TR' + \$C)$ $+ 0.1 (\$F_1 + \$C_1 + \$TR)$	SD system and receiver front end with NF = 0.5 db (or 1.0 db)
2. AOC for MA	$\$MO = 0.2 (\$MA + \$C) + 0.1 (\$TDU + \$C_1)$ $+ 0.1 [4LC (\$TR' + \$F_1^*)]$	MA system and receiver front end with NF = 0.5 (or 1.0 db) LC = learning curve factor = 0.9025
3. AOC for QA	$\$MO = 0.2 (\$QA + \$C) +$ $0.1 [\$TR'' + 4 LC (\$F_1^*) + \$C_1]$	QA system and receiver front end with NF = 0.5 db (or 1.0 db); LC = learning curve factor = 0.9025
MA Antenna Model	$\$MA = 4LC [\$A + \$E] + \$TDU$ where, $\$E = \$TR' + (\$F_1^*)$	MA system and receiver front end with NF = 0.5 db (or 1.0 db) LC = 0.9025; see equation (16)
QA Antenna Model	$\$QA = 4LC (0.35 \$A_1 + \$F_1^*)$ $+ 0.65 \$A_2$ $+ \$TR''$	QA system and receiver front end with NF = 0.5 db (or 1.0 db) LC = 0.9025; see equation (17)
<u>Total System Cost Models</u>		
$\$F_1^* = \$F_1$ or $\$F_1'$ ; Y = Write-off period = 15 years; i = discount Rate = 0.1		
SD	$\$TSD = \text{Investment Costs} + \text{AOC Costs} = \$A + \$F_1^* + \$TR' + \$C + \$R \text{ (if needed)} + \sum_{y=1}^{15} \frac{\$MO}{(1+i)^y}$	
MA	$\$TMA = 4LC [\$A + \$E] + \$TDU + \$C + \sum_{y=1}^{15} \frac{\$MO}{(1+i)^y}$	
QA	$\$TQA = 4LC [0.35 \$A_1 + \$F_1^*] + 0.65 \$A_2 + \$TR'' + \$C + \sum_{y=1}^{15} \frac{\$MO}{(1+i)^y}$	

## CHAPTER 5

### TRADE-OFF (COST SENSITIVITY) ANALYSIS

This chapter will be divided into two main sections: the cost-effectiveness analysis as it relates to the antenna and the basic electronics package and the cost-benefit analysis as it relates to the total system costs. The analyses will be conducted on three different ground station configurations, viz., the single dish (SD) system, the quad-array (QA) system and the multiple-aperture (MA) system.

#### 5.1 Cost-Effectiveness Analysis

Using the cost models developed in Section 4.3 a single criterion will be investigated to determine its appropriateness to the specified effectiveness model; this criterion is: the maximum cost-effectiveness antenna for a specified antenna gain and frequency.

Maximum Cost-Effectiveness Antenna: The maximum cost-effectiveness antenna is defined as one which provides the maximum gain per °K (effectiveness) per dollar of cost at the required gain. Since gain is a function of diameter and since cost varies as a function of reflector surface tolerance and diameter, a set of parametric curves can be plotted relating antenna gain, system noise temperature and surface tolerance to cost and antenna effectiveness. Thus, the following set of curves will be generated:

- (1) Gain-Cost Versus Gain Curves for Two Antenna Models (without electronics).

These curves will show which model is most appropriate as a function of gain.

(2) Cost-Effectiveness Curves for the SD System with Receiver Front-Ends having NF's of 1.0 db and 0.5 db. These curves will show which front-end is most cost-effective as a function of gain.

(3) Cost-Effectiveness Curves for the QA System with Receiver Front-Ends having NF's of 1.0 db and 0.5 db. The same comment applies here as for curves in (2).

(4) Cost-Effectiveness Curves for the MA System with Receiver Front-Ends having NF's of 1.0 db and 0.5 db. Comments are same as for curves in (2) and (3).

(5) Cost-Effectiveness Curves for SD, QA and MA Systems with Receiver Front-End Having a NF of 0.5 db. These curves will show which antenna system is most cost-effective as a function of gain.

(6) Cost-Effectiveness Curves for SD, QA and MA Systems with Receiver Front-End having a NF of 1.0 db. Comment on curves in (5) applies here as well.

(7) Cost-Effectiveness Curves for SD System Considering a Radome and a Front-End Having a NF of 0.5 db. These curves will show which antenna system is most cost-effective as a function of gain.

(8) Cost-Effectiveness Curves for SD System Considering a Radome and a Front-end having a NF of 1.0 db. Comments are same as for curves shown in (7).

Gain-Cost Versus Gain Curves: The equations used for developing the values for the graph in Figure 8 are the following:

$$C E_0 = \frac{\eta (a_4 D f)^2 e^{-(a_5 \sigma f)^2}}{a_1 D^{-1/3} e^{D/45}} = \text{equation (13.3)} \quad (18.1)$$

where,

$C E_0$  = gain-cost value in absolute units of gain per dollar. The other terms were defined in equations (13.3) and (9).



$$C E_1 = \frac{G = \text{equation (13.3)}}{\$_0 e^{(x_1-1)} = \text{equation (12.2)}} \quad (18.2)$$

where,  $X_1$ , is related to the value of  $\gamma$  as defined in equation (5). For the GSFC model  $\gamma = 10^{-4.52}$ . The symbol  $e$  is the base number 2.718.

Table VIII is a tabulation of data used for generating the curves in Figure 10.

Cost-Effectiveness Curves for the SD System: The equation used for developing the values for Figure 11 is the following:

$$C E_{SD}^* = \frac{G = \text{equation (13.3)}}{\{[\$_A = \text{equation (13.2)}] + \$_{F1}^* + T_R^1\} T_s^*} \quad (19)$$

where,  $T_s^* = (T_{s1} \text{ or } T_{s2})$  is system noise temperature for receiver having a front-end with a NF of 1.0 db or NF of 0.5 db.  $\$_{F1}^*$  is cost of preamplifier NF = 1.0 db or NF = 0.5 db, and  $T_R^1$  is cost of tracking receiver. Other terms were defined previously.

Table IX is a tabulation of data used for generating the curves in Figure 11.

Cost-Effectiveness Curves for the MA System: The following equation was used for obtaining curves plotted in Figure 12:

$$C E_{MA}^* = \frac{G = \text{equation (13.3)}}{[\$_{MA} = \text{equation (16)}] T_s^*} \quad (20)$$

Cost-Effectiveness Curves for the QA System: The equation pertinent to graphs generated in Figure 13 is:

$$C E_{QA}^* = \frac{G = \text{equation (13.3)}}{[\$_{QA} = \text{equation (17)}] T_s^*} \quad (21)$$

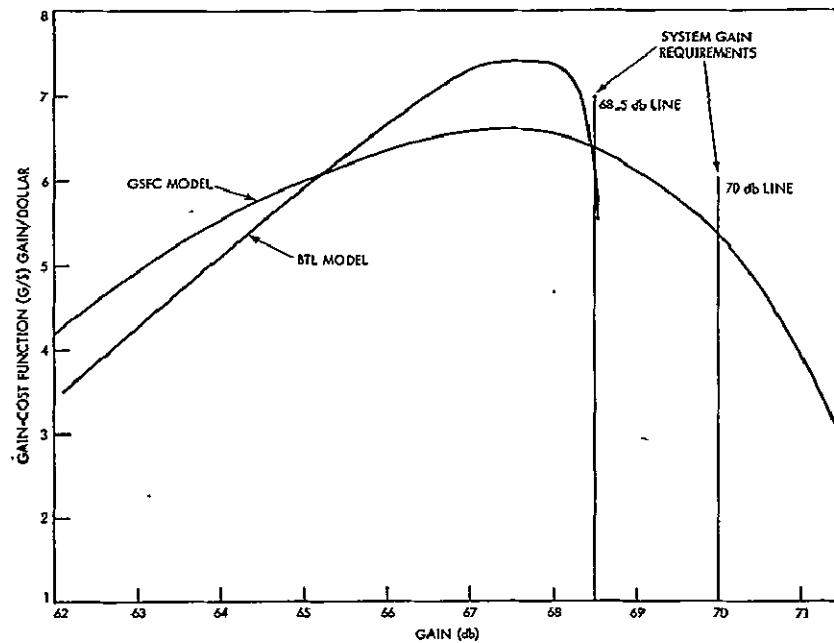


Figure 10. Gain-Cost Curves for Two Antenna Models,  
Without Electronics

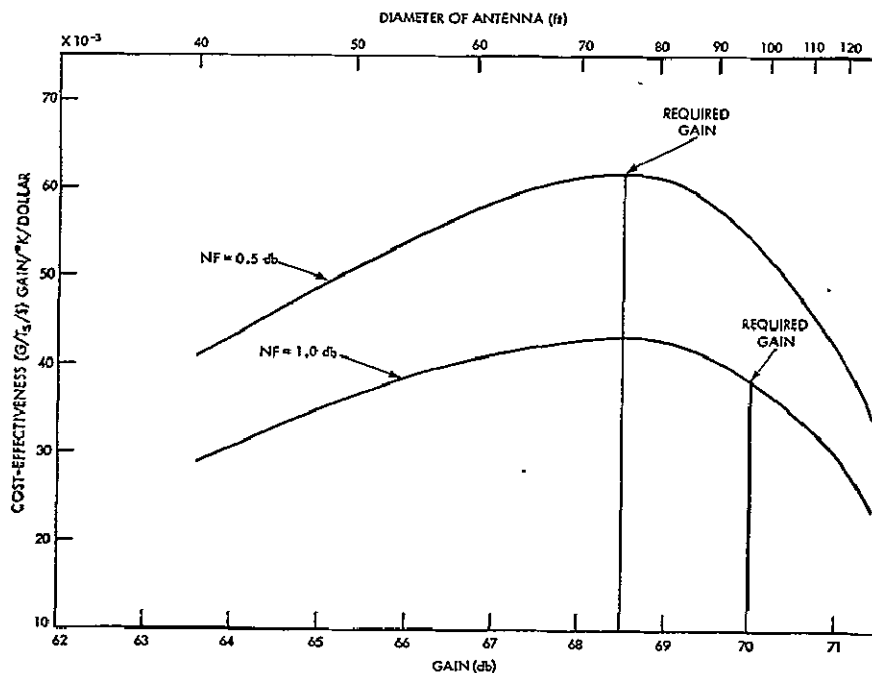


Figure 11. Cost Effectiveness Curves for the SD System With  
Two Different Preamplifier Designs: One Having a  $NF = 1.0$   
db and the Other Having a  $NF = 0.5$  db.

Table VIII

Gain-Cost Values of Two Antenna Models Without Electronics  
for 16 GHz for Various Gains and Diameters

Diameter of Reflector	GSFC Model				BTL Model			
	Gain		Cost(1) of Antenna $\times 10^6$	Gain-Cost G/\$	Gain		Cost(2) of Antenna $\times 10^6$	Gain-Cost G/\$
	db	Abs $\times 10^6$			db	Abs $\times 10^6$		
30	61.2	1.315	0.374	3.52	61.7	1.34	0.424	3.15
40	63.6	2.28	0.425	5.35	63.7	2.31	0.476	4.85
50	65.4	3.43	0.554	6.16	65.3	3.38	0.553	6.11
60	66.8	4.78	0.725	6.66	66.7	4.63	0.638	7.26
70	68.0	6.2	0.936	6.62	67.6	5.74	0.771	7.44
80	68.9	7.6	1.19	6.46	68.3	6.7	0.920	7.3
90	69.6	9.05	1.57	5.81	68.5	7.12	1.10	6.47
100	70.2	10.5	2.04	5.15	68.6	7.25	1.33	5.45
110	70.7	11.8	2.55	4.66	68.5	7.11	1.62	↑ Data Beyond the gain- limit point ↓
120	71.1	12.9	3.38	3.84	68.0	6.24	1.95	
130	71.4	13.8	4.35	3.18	67.1	5.05	2.36	
140	71.7	14.6	5.6	2.28	66.1	4.05	2.88	
150	71.8	15.1	7.2	2.09	64.9	3.06	3.53	
160	71.82	15.2	9.59	1.65	63.3	2.1	4.31	

Notes: 1. Cost function for the GSFC model is the following:

$$\$_4 = [a_1 D^{-1/3} e^{D/45}] e^{(X_1-1)} = \$_0 e^{(X_1-1)} = \text{equation (12.2)}$$

$$\text{where, } X_1 = 0.142 D^{0.5}$$

2. Cost function for the BTL model is the following:

$$\$_0 = \text{equation (9); where } X_1 = 1.$$

Table IX

Cost Effectiveness Values for the SD System with Electronics  
for 16 GHz for Various Gains and Diameters

Diameter (ft)	Gain <sup>(1)</sup> (db)	Costs of Antenna, Pre-amps and Tracking Receiver <sup>(1)</sup> for Receiver with different NF's		Antenna Effectiveness <sup>(2)</sup> (AE*) for Different Receiver NF's		Cost Effectiveness <sup>(3)</sup> (G/T <sub>s</sub> <sup>*</sup> /\$) for Different Receiver NF's	
		NF = 1.0 db \$X10 <sup>6</sup>	NF = 0.5 db \$X10 <sup>6</sup>	NF = 1.0 db G/T <sub>s1</sub> X10 <sup>3</sup>	NF = 0.5 db G/T <sub>s2</sub> X10 <sup>3</sup>	NF = 1.0 db CE <sub>SD1</sub> X10 <sup>-3</sup>	NF = 0.5 db CE <sub>SD2</sub> X10 <sup>-3</sup>
30	61.2	0.57	0.584	10.35	15	18.1	25.7
40	63.6	0.62	0.635	18.0	26	29.0	41.0
50	65.4	0.75	0.764	27.0	39	36.0	51.0
60	66.8	0.92	0.935	37.6	54.4	40.8	58.0
70	68.0	1.13	1.15	48.8	70.5	43.1	61.3
80	68.9	1.39	1.4	60.0	86.5	43.1	61.6
90	69.6	1.77	1.78	71.3	103	40.2	58.0
100	70.2	2.24	2.25	82.6	119	37.0	53.0
110	70.7	2.75	2.76	93	134	34.0	48.5
120	71.1	3.58	3.59	102	147	28.6	41.0
130	71.4	4.55	4.56	109	157	24.0	34.2
140	71.7	5.80	5.81	115	166	19.8	28.6
150	71.8	7.40	7.41	119	171	16.1	23.1
160	71.82	9.79	9.8	120	173	12.3	17.6

Notes: 1. The costs, \$<sub>A</sub>, and the gains G, are related to the GSFC model, viz.,

$$\$_A = \$_0 e^{(X-1)} \text{ where, } X = 0.142 D^{0.5} \quad (12.2)$$

$$G = \eta (a_4 Df)^2 e^{-(\sigma_5 \sigma f^2)} \text{ where, } \sigma = 3.6 \times 10^{-4} D \quad (13.3)$$

The total costs are as follows:

$$\$_A + (\$_{F1} \text{ or } \$_{F1}') + T_R'$$

where

$$\$_{F1} = \$65,000, \text{ sum receiver (NF = 1.0 db),}$$

$$\$_{F1}' = \$80,000, \text{ sum receiver (NF = 0.5 db), and}$$

$$T_R' = \$130,000, \text{ tracking receiver}$$

2. The system noise temperature, T<sub>s</sub><sup>\*</sup>, is calculated for clear sky weather conditions and for an antenna elevation angle of 30 degrees. T<sub>s</sub><sup>\*</sup> can be expressed as:

$$T_s^* = \alpha T_a + 290 (1 - \alpha) + 290 (NF_{1,2} - 1)$$

where,  $\alpha = 0.89$ , NF<sub>1</sub> = 1.0 db and NF<sub>2</sub> = 0.5 db and T<sub>a</sub> = T<sub>1</sub> + T<sub>2</sub> (see note 1, Table IV)

Thus, T<sub>s1</sub> = 127°K and T<sub>s2</sub> = 88°K; note T<sub>s</sub><sup>\*</sup> = T<sub>s1</sub> or T<sub>s2</sub>

3. The cost-effectiveness equation is given in the text, see equation (19).

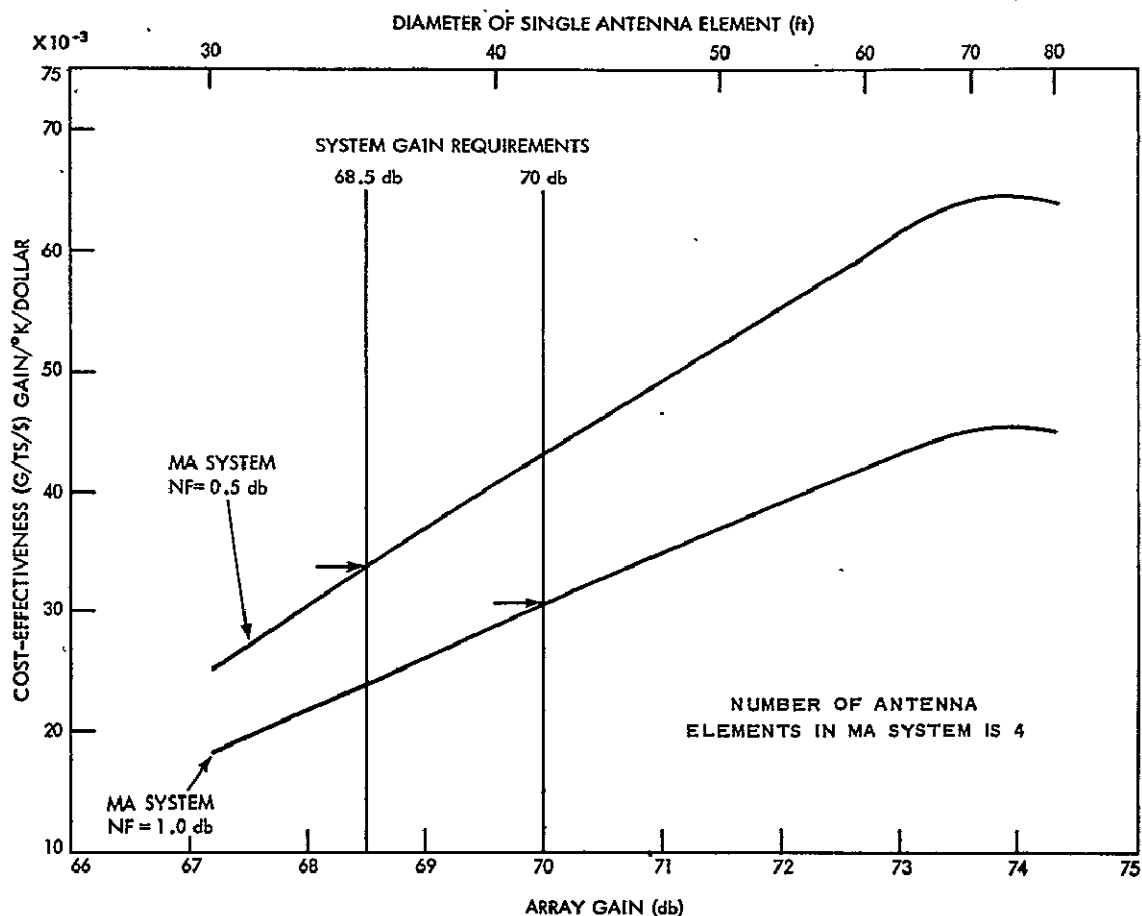


Figure 12. Cost Effectiveness Curves for the MA System With Two Different Preamplifier Designs: One Having a NF = 1.0 db and the Other Having a NF = 0.5 db.

Tables X and XI are tabulations of data used for plotting graphs shown in Figures 12 and 13, respectively.

Composite Cost-Effectiveness Curves for TDRS Ground Station: The information for these curves is available in Tables IX, X and XI. The plots for receiver systems with 0.5 db NF and 1.0 db NF are shown in Figures 14 and 15, respectively. For the preamplifier with 0.5 db NF, the criterion is the highest cost-effectiveness value for an antenna gain of 68.5 db, and for a preamplifier with 1.0 db NF, the criterion is the highest cost-effectiveness value for an antenna gain of 70.0 db.

Table X

Cost Effectiveness Values for the MA System, With Electronics,  
For Various Gains and Diameters

Diameter of Single Antenna Element (Array of four) (ft)	Gain of <sup>(2)</sup> Equivalent Single Antenna		Cost of Antenna and Receiver Systems for Receivers with different Noise Figures ( $\$ \times 10^6$ ) <sup>(1)</sup>		Cost-Effectiveness, $G/T_s^*/\$,$ for each type of receiver system considered <sup>(3)</sup>	
	(ABS $\times 10^6$ )	(db)	NF = 1.0 db	NF = 0.5 db	NF = 1.0 db (ABS/ $^{\circ}$ K/ $\$$ ) $\times 10^{-3}$	NF = 0.5 db (ABS/ $^{\circ}$ K/ $\$$ ) $\times 10^{-3}$
30	5.25	67.2	2.28	2.35	18.2	25.4
40	9.1	69.6	2.47	2.53	29.0	40.8
50	13.7	71.5	2.94	2.99	36.8	52.2
60	18.7	72.7	3.505	3.565	42	60
70	24.8	73.9	4.275	4.335	45.6	65
80	30	74.8	5.265	5.325	45	64

Notes: 1. The costs,  $\$_{MA}$ , are related to the model developed in Section 4.3, Multiple-Aperture Model, viz.,

$$\$_{MA} = N (0.95 \cdot 10^{0.2N}) [\$_A + \$_E] + \$_{TDU} \quad (16)$$

where: (a)  $\$_A = \$_0 e^{(X-1)}$  (equation 12.2). Note  $X = 0.142 D^{0.5}$  for antenna elements

$$(b) \$_E = \$'_{TR} + (\$'_{F1} \text{ or } \$_{F1}) = \$130,000 + \$ (65,000 \text{ or } 80,000)$$

$\$65,000$  = cost of receiver (NF = 1.0 db)

$\$80,000$  = cost of receiver (NF = 0.5 db)

$$(c) \$_{TDU} = \text{Time Delay Unit} = \$225,000$$

2. The gain of MA is calculated by using equation (13.3) and adjusted for the GSFC model for the array elements

$$G = \eta (a_4 Df)^2 e^{-(a_5 \sigma f^2)} \text{ where } \sigma = 3.6 \times 10^{-4} D$$

ABS denotes antenna gain is calculated in absolute units

3. The system noise temperature,  $T_s^*$ , is calculated for a 30 degree elevation angle and clear sky weather conditions.  $T_{s1} = 127^{\circ}\text{K}$  (related to receiver with NF = 1.0 db) and  $T_{s2} = 88^{\circ}\text{K}$  (related to receiver with NF = 0.5 db).

The  $T_s^*$  calculations are identical to those described in Table IX, Note 2 and Table IV, Note I.

The cost-effectiveness equation is given in the text, see equation (20):

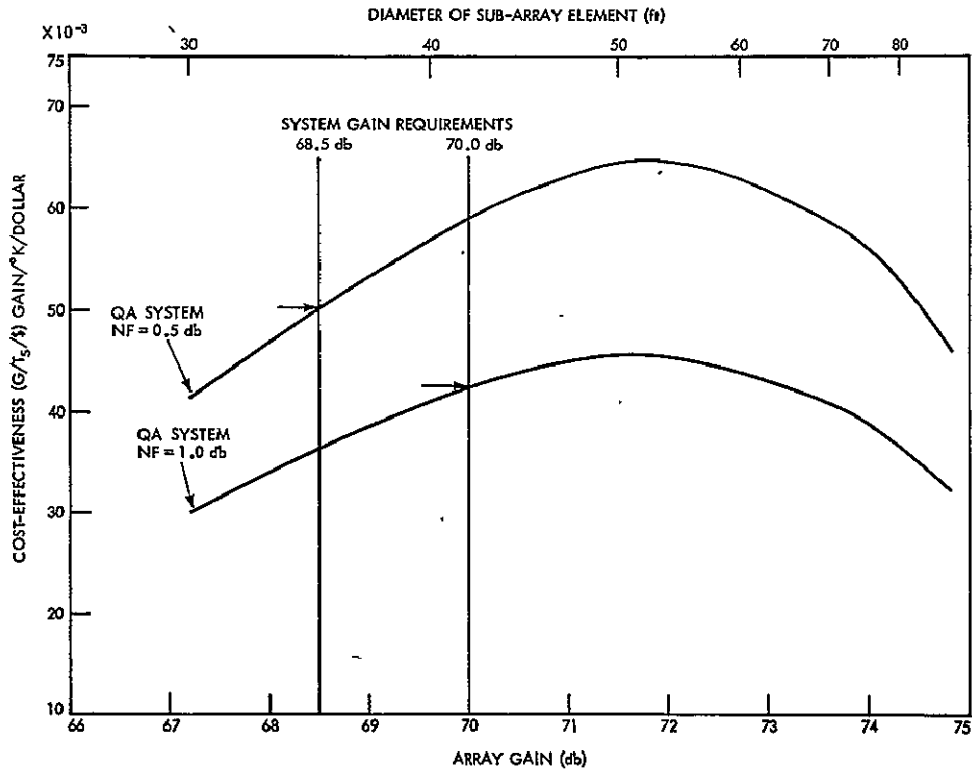


Figure 15. Cost Effectiveness Curves for the QA System with Two Different Preamplifier Designs: One Having a NF = 1.0 db and the Other Having a NF = 0.5 db.

Cost-Effectiveness Curves for an Exposed SD System and a Radome Enclosed SD System: The equations used for showing the trade-off between an exposed antenna and a radome enclosed antenna are equation (19) and the following equation:

$$C E_{SDR}^* = \frac{G_{AR} = (\text{equation 14.3})}{\{[\$_{AR} = (\text{equation 14.2})] + (\$_{F1}^* + T_R^1)\} T_s^*} \quad (22)$$

where, all terms were previously defined. Two sets of curves are presented in this analysis. Figure 16 shows the cost effectiveness curves for the case when the pre-amplifier NF is 0.5 db and Figure 17 depicts the cost-effectiveness curves for the case when the preamplifier NF is 1.0 db. Table XII contains the data for generation of curves illustrated in Figures 16 and 17.

Table XI

Cost Effectiveness Values for the QA System with Electronics,  
for Various Gains and Diameters

Diameter of Sub-Array Element in feet. The array number is four (Eq. Pedestal)	Gain of Array (Equivalent to Single Antenna <sup>(2)</sup> )		Cost of Antenna and Receiver System for Receivers with different Noise Figures ( $\$ \times 10^6$ ) <sup>(1)</sup>		Cost-Effectiveness, $G/T_s^*/\$,$ for each type of receiver system considered <sup>(3)</sup>	
	(ABS $\times 10^6$ )	(db)	NF = 1.0 db	NF = 0.5 db	NF = 1.0 db (ABS/ $^{\circ}$ K/ $\$$ ) $\times 10^{-3}$	NF = 0.5 db (ABS/ $^{\circ}$ K/ $\$$ ) $\times 10^{-3}$
30 ( 75)	5.25	67.2	1.386	1.44	30.0	41.5
40 (100)	9.1	69.6	1.742	1.80	41.1	57.2
50 (125)	13.7	71.5	2.36	2.41	45.8	64.7
60 (150)	18.7	72.7	3.33	3.38	44.1	63
70 (175)	24.8	73.9	4.89	4.94	40	57
80 (200)	30.0	74.8	7.24	7.29	32.7	46.7

Notes: 1. The costs,  $\$_{QA}$ , are related to the model developed in Section 4.3, Quad-array Model, viz.,

$$\$_{QA} = N(0.95^{10 \log_2 N}) [0.35 \$_{A1} + (\$_{F1} \text{ or } \$'_{F1})] + 0.65 \$_{A2} + \$''_{TR} \quad (17)$$

where: (a)  $\$_{A1} = \$_0 e^{(X-1)}$  (equation 12.2) and  $X = 0.142 D^{0.5}$  for GSFC model

(b)  $\$_{A2} = \$_0$  (equation 9), and  $X = 1$ ,

(c)  $\$_{F1} = \$65,000$ , cost of front end (NF = 1.0 db) and

$\$'_{F1} = \$80,000$ , cost of front-end (NF = 0.5 db),

(d)  $\$''_{TR} = \$160,000$ , cost of tracking receiver.

2. The gain of the QA system is calculated by using equation (13.3) and adjusted for the GSFC Model viz.,

$$G = \eta (a_4 D f^2) e^{-(a_5 \sigma f^2)} \quad \text{where, } \sigma = 3.6 \times 10^{-4} D$$

ABS denotes antenna gain is measured in absolute units

3. The system noise temperature,  $T_s^*$ , ( $T_s^* = T_{s1}$  or  $T_{s2}$ ) is calculated as stated in Table IV, Note 1 and Table IX, Note 2.

The cost-effectiveness equation is given in the text, see equation (21).



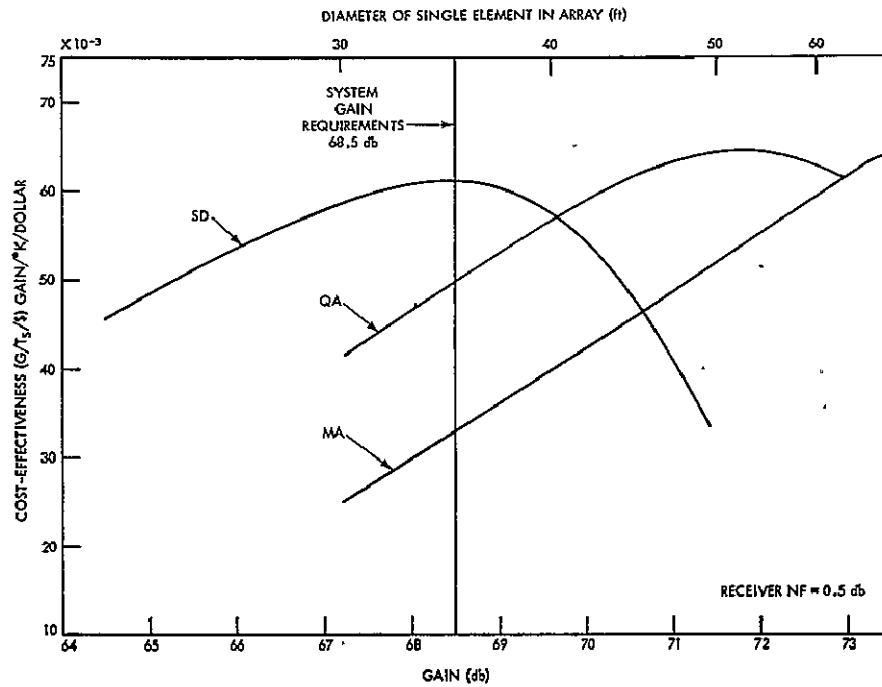


Figure 14. Composite Cost-Effectiveness Curves for the Three Ground Station Configurations with a Pre-amplifier Having a  $NF = 0.5$  db.

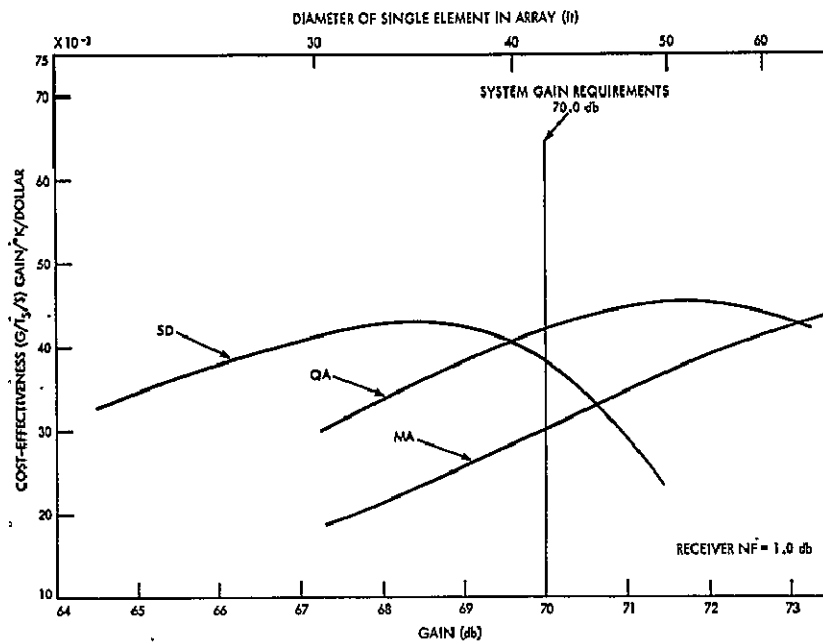


Figure 15. Composite Cost-Effectiveness Curves for the Three Ground Station Configurations with a Pre-amplifier Having a  $NF = 1.0$  db.

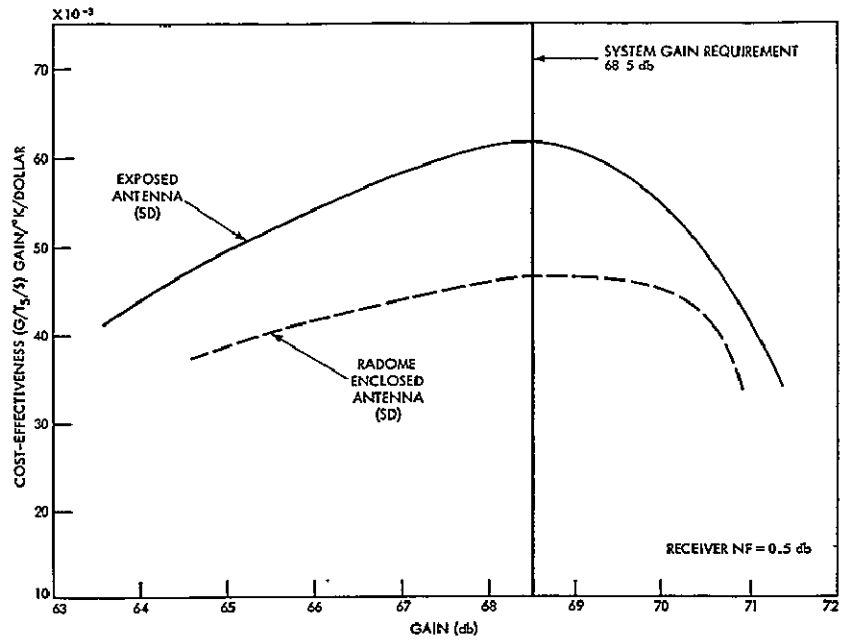


Figure 16. Cost-Effectiveness Curves for SD System Considering a Radome and a Preamplifier with a NF of 0.5 db.

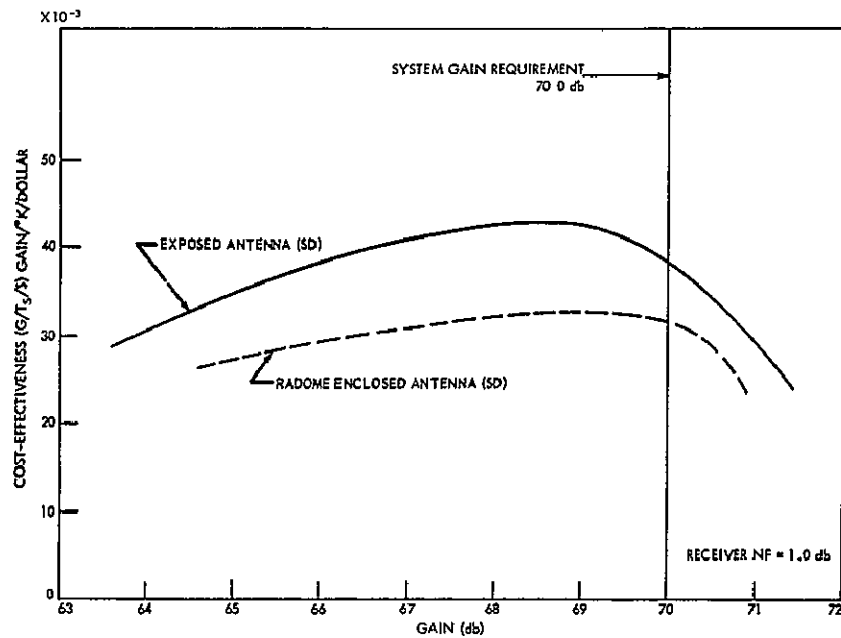


Figure 17. Cost-Effectiveness Curves for SD System Considering a Radome and a Preamplifier with a NF of 1.0 db.

Table XII

Cost Effectiveness Values for the SD System With Electronics,  
and Radomes for Various Gains and Diameters

Diameter (ft)	Gain <sup>(2)</sup>		Cost of Antenna, Radome and Receiver System for Receivers with Different Noise Figures (\$X 10 <sup>6</sup> ) <sup>(1)</sup>		Cost-Effectiveness, G/T <sub>s</sub> */\$, for each type of receiver system considered <sup>(3)</sup>	
	(ABS X 10 <sup>6</sup> )	(db)	NF = 1.0 db	NF = 0.5 db	NF = 1.0 db (ABS/°K/\$) X 10 <sup>-3</sup>	NF = 0.5 db (ABS/°K/\$) X 10 <sup>-3</sup>
30	1.09	60.4	0.503	0.518	17	24
40	1.88	62.7	0.666	0.671	22.2	31.9
50	2.84	64.6	0.852	0.867	26.2	37.2
60	3.93	65.9	1.06	1.075	29.2	41.5
70	5.09	67.5	1.285	1.3	31.2	44.5
80	6.28	68	1.535	1.55	32.2	46.0
90	7.46	68.7	1.795	1.81	32.8	46.9
100	8.57	69.3	2.085	2.1	32.4	46.4
110	9.59	70	2.375	2.39	31.8	45.6
120	10.46	70.2	2.695	2.71	30.5	44.0
130	11.18	70.5	3.025	3.04	29.8	41.8
140	11.7	70.7	3.365	3.38	27.4	39.4
150	12.06	70.8	3.725	3.74	25.5	36.7
160	12.21	70.9	4.105	4.12	23.5	33.8

Notes: 1. The costs, \$<sub>AR</sub>, are related to the model developed in Section 4.3 Single Dish (Enclosed Antennas), viz.,

$$\$_{AR} = e^{(X-1)} [a_2 D^{1.3} - B_3 D^{1.85}] + B_3 D^{1.85} \quad (14.2)$$

where, X for the GSFC model is 0.142 D<sup>0.5</sup>

The costs of the electronics has been previously stated, see Table IX, Note 1.

2. The gain, G<sub>AR</sub>, is related to model mentioned above and is expressed as follows:

$$G = \frac{n}{L} (B_4 Df)^2 e^{-(B_5 \sigma f)^2} \quad (14.3)$$

where, L = 1.26, the assumed attenuation less and  $\sigma = 0.142 D^{0.5}$ , see Table IX, Note 1.

ABS denotes antenna gain is measured in absolute units

3. System noise temperature is assumed to be T<sub>s1</sub> = 127°K and T<sub>s2</sub> = 88°K, see Table IV, Note 1.

The cost-effectiveness equation is given in the text, see equation (22).

Summary of Results of the Cost-Effectiveness Analysis: In studying the curves related to the cost-effectiveness analysis, several observations can be made:

(1) Cost-Effective Antenna Model. Two different cost models were considered; these were: (a) the standard cost model as represented by the BTL approach and (b) the GSFC model as determined by a survey conducted by Stack in his studies of large parabolic antennas (see reference 21). It was found that the GSFC model was most appropriate in the gain region of interest, viz., the region between 62 db and 65.2 db, where small reflectors can be used in an array, and in the gain region between 68.4 db and 70.7 db where a single large reflector can be considered as a possible candidate to meet system requirements (see Figure 10).

(2) Single Dish (SD) System. After establishing the appropriate antenna model, a trade-off between two different front end designs was made. It was found that the receiving system with the "cooler" front-end, viz., the one with a NF of 0.5 db was preferable (see Figure 12). The cost-effectiveness (CE) value for the system with 0.5 db preamplifier was  $61.8 \times 10^{-3}$  and the CE value for the system with a preamplifier having a 1.0 db NF was  $38.5 \times 10^{-3}$ , a ratio of 1.6 to one. It should be noted that two system gain requirements can achieve the required 30 db CNR, viz., a 68.5 db effective antenna gain when the receiver system uses a front-end with a NF of 0.5 db and a 70 db effective antenna gain when the receiver system uses a front-end with a NF of 1.0 db. As stated above, the "cooler" receiving system is the more cost-effective system.

(3) Multiple Aperture (MA) System. Figure 13 shows that the two receiving systems have about the same CE values. The CE value for the 0.5 db system is  $33.5 \times 10^{-3}$  and the CE value for the 1.0 db system is  $31.5 \times 10^{-3}$ . A study of the cost factors should uncover the basic reason for the system behavior. Sensitivity can be defined

as the ratio of percentage change of the function, CE, to percentage change in a system parameter,  $\$_{F1}$ . Symbolically, it can be expressed as:

$$S_{CE}^{\$_{F1}} = \Delta CE / CE / \Delta \$_{F1} / \$_{F1} = \frac{\Delta CE}{CE} \left( \frac{\$_{F1}}{\Delta \$_{F1}} \right) \quad (23)$$

where,

$\Delta CE$  is incremental change in CE,

$\Delta \$_{F1}$  is incremental change in cost of preamplifier, and CE and  $\$_{F1}$  have been previously defined.

Thus, a 19 percent change in receiver costs results only in a 6 percent change in system cost-effectiveness. It is believed that the basic reason for the low sensitivity to the preamp choice lies in the fact that costs of the electronics in the MA system are a large portion of the overall costs. A reduction in system noise lowers the gain requirements by 1.5 db and correspondingly, reduces the antenna size from 42 feet to 36 feet. At the same time, the costs of the front-end increases from \$65,000 to \$80,000. Thus, the structure costs are lowered by \$63,000 per array element or a percentage change of 14 while the electronics costs are increased by \$15,000 per array element or a percentage change of 19. Consequently, the costs savings and increases virtually balance each other on the evaluation scale which has a base cost for the total system of  $2.6 \times 10^6$  dollars.

(4) Quad-Array (QA) System. Figure 13 presents the CE curves for the two receiving systems considered. It was found that the "cooler" of the two receiving systems, i.e., the preamp with the NF of 0.5 db, is preferable. The percentage change in CE value is 18; note, the 0.5 db system has a CE value of 50 and the 1.0 db system has a value of 42.5. Although, some sensitivity to the selection of the receiving system is noticeable, it is still not as sharply defined as in the SD system. The reason for this system behavior can be ascribed to the dominant role played by the electronics costs,

as in the MA system. The "MA" effect is not so clearly pronounced in the QA system because only a portion of the antenna system, viz., 35 percent has the multiple electronic costs associated with it, see equation (17).

(5) Analysis of the Composite CE Curves. The Figures 14 and 15 show the CE performance of the three systems, viz., the SD, MA and QA systems, as a function of system gain. In considering the 0.5 db receiving system (see Figure 14), it was found that the SD system has the highest CE value of the three configurations for the required system gain. One interesting point, the SD system has reached its peak CE value at 68.5 db gain and can be considered operating at its optimum point. The QA system, however, does not reach its maximum CE value until the gain is 71.5 db. Consequently, if gain requirements in the future are increased, the QA system will become more cost-effective than the SD or the MA system. Beyond 72.6 db gain point, the MA system begins to become the cost-effective system. In considering the 1.0 db receiving system (see Figure 15), it was found that the QA system has a slightly greater CE value than the SD system; the CE value for the QA system is  $42.5 \times 10^{-3}$  and the CE value for the SD system is  $38 \times 10^{-3}$  for the required system gain. The difference is an 11 percent improvement in CE for the QA system over a comparable SD system.

(6) Analysis of the SD system With Radome Considerations. Figures 16 and 17 show the CE performance of the SD system when a radome is included in the system. The CE curves are drawn for the two front end designs considered. From a study of the CE curves, it is clear that in the region of interest the antenna enclosed in a radome is always less cost-effective than the exposed antenna system. Basically, the reason for this result can be ascribed to the 1.0 db loss associated with the radome. In large dish systems requiring high efficiencies, even operating well below the gain limit point, the cost to achieve a one db increase in antenna gain is very high; in the TDRS case, it requires about a 20 percent increase in dish diameter to increase the gain of an antenna system from 70 db to 71 db.

## 5.2 Cost-Benefit Analysis

The previous section in this chapter developed the CE models for the three ground station configurations considered, viz., the SD, MA and QA antenna systems. In this section, a cost-benefit study will be made on the three station models to determine the following:

- (1) the present worth and equivalent annual cost for subsequent economic analyses, and
- (2) the return-on-investment and break-even point analyses for three ranges of network reductions.

Prior to analyzing the appropriate station configurations, several key assumptions should be explicitly stated. These assumptions are as follows:

- (1) The TDRS network requirements for real-time global coverage will exist for both the low- and the high-data rate user with an availability of 0.998.
- (2) As the TDRS networks become more proficient operationally, existing MSFN and STADAN stations will be phased out according to the maximum cost-benefit ratio. The procedure for establishing the comparative bases for evaluations will be set forth in assumption (4).
- (3) The station equipment cost estimates used in the cost-benefit analysis are taken from a cost-effectiveness study conducted internally at GSFC.<sup>47</sup>
- (4) The investment opportunities associated with the various station configurations will be evaluated according to the criteria established by the following analytical techniques:

- (a) Return-on-Investment (ROI) Analysis. The ROI evaluation scheme measures the station operation savings as a fraction of the amount invested. The

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<sup>47</sup> Moye, et al, Cost Effectiveness Analysis of Telemetry Data Acquisition by the Space Tracking and Data Acquisition Network (STADAN) (GSFC X-520-69-275, July 1969), p. 21.

basis selected for establishing the yardstick comparison is the discounted-cash-flow-(DCF) basis.<sup>48,49</sup> The DCF method finds the equivalent discount rate which if applied to each year's estimated station savings, would make the combined present worth of these savings equal to the initial investment cost.<sup>50</sup> The ROI model chosen as the standard for comparison is based on the following assumption. Capital will be invested for a 15 year period at a 10 percent return rate.

(b) Break-Even Point (BEP) Analysis. The BEP is defined as that point in time where the investment is fully recovered. The total investment in the establishment of the TDRS ground stations is the difference in the operational costs of the MSFN and STADAN antennas with TDRS and the operational costs of the network antennas without TDRS.

#### Development of The Present Worth (PW) and The Equivalent Annual Cost (EAC)

Values: From the analysis performed in Section 3.1, it was found that two different receiving systems can achieve the appropriate level of effectiveness. In using the receiving system which has a front-end with a 0.5 db NF, the system gain requirement is 68.5 db and in using the receiving system which has a front-end with a 1.0 db NF, the system gain requirement is 70.0 db. Table XIII below lists the investment and the annual M&O costs per station, for each system gain requirement considered. The assumptions regarding discount rate, equipment life cycle, salvage value and percentage of investment

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<sup>48</sup> William T. Morris, The Analysis of Management Decisions (Homewood, Illinois, Richard D. Irwin, Rev. Ed. 1964), p. 69.

<sup>49</sup> William D. Brinckloe, Managerial Operations Research (New York: McGraw-Hill 1969), p. 101.

<sup>50</sup> James C. Hetrick, "Mathematical Models in Capital Budgeting" (Harvard Business Review, January/February 1961), p. 49.



Table XIII

Summary of Station Costs Associated with the SD, MA and QA Systems  
for the Two Receiver Systems Considered

## A. The 0.5 db Receiver System (System Gain Requirement is 68.5 db).

Station Configuration	Antenna System Costs (I) $\times 10^6$	Operations Costs (0.2I) $\times 10^6$	Annual Equipment Costs (0.1I <sub>1</sub> ) $\times 10^6$	Total Costs per Station $\times 10^6$ Y = Write-off period
SD System <sup>(1)</sup> 1-77 ft. reflector	1.91	.381	.044	1.91 + .425Y
MA System <sup>(2)</sup> 4-36 ft. reflectors	3.14	.628	.121	3.14 + .749Y
QA System <sup>(3)</sup> 4-36 ft. reflectors	2.39	.479	.067	2.39 + .546Y

## B. The 1.0 db Receiver System (System Gain Requirement is 70 db)

SD System <sup>(4)</sup> 1-97 ft. reflector	2.8	.56	.042	2.8 + .602Y
MA System <sup>(5)</sup> 4-42 ft. reflectors	3.3	.66	.116	3.3 + .776Y
QA System <sup>(6)</sup> 4-42 ft. reflectors	2.65	.531	.062	2.65 + .593Y

## Notes

1. The costs related to the SD system are shown in Table IX and can be expressed as follows:

## (a) Antenna and Receiver Costs:

$$(\$_A = \$960,000) + (\$'_{F1} = \$80,000) + (\$'_{TR} = \$130,000) + (\$_C = \$735,000)$$

## (b) Operations Costs:

$$0.2 (\$_A + \$'_{F1} + \$'_{TR} + \$_C)$$

## (c) Annual Equipment Costs:

$$0.1 (\$'_{F1} + (\$'_{C1} = \$225,000) + \$_{TR})$$

2. The costs related to the MA system are shown in Table IX and can be expressed as follows:

(a) Antenna and Receiver Costs ( $\$_{MA}$ ):

$$(a.1) \ 4 (0.9025) (\$_A + \$'_{TR} + \$'_{F1}) + \$_{TDU}$$

where,  $\$_A = \$391,000$  (Antenna system)

$\$'_{TR} = \$130,000$  (Tracking receiver)

$\$'_{F1} = \$80,000$  (Preamplifier)

$\$_{TDU} = \$225,000$  (Time Delay Unit)

(a.2) Command System Costs ( $\$_C$ ):

$$\$_C = \$735,000$$

## (b) Operations Costs:

$$(1) \ 0.2 (\$_{MA} + \$_C) = \$628 \times 10^6$$

## (c) Annual Equipment Costs:

$$0.1 (\$_{TDU} + \$_{C1}) + 0.1 [3.61 (\$'_{TR} + \$'_{F1})]$$

where,  $\$_{C1} = \$225,000$  (Transmitter)

3. The costs related to the QA system are shown in Table VII and can be expressed as follows:

(a) Antenna and Receiver Costs ( $\$_{QA}$ ):

$$(a.1) \ 3.61 (0.35 \$_{A1} + \$'_{F1}) + 0.65 \$_{A2} + \$'_{TR}$$

where,  $\$_{A1} = \$391,000$  (36 foot reflector)

$\$'_{F1} = \$80,000$  (Preamplifier)

$\$_{A2} = \$1,100,000$  (90 foot base and backup structure)

$\$'_{TR} = \$160,000$  (Tracking Receiver)

## (a.2) Command System Costs

$$\$_C = \$735,000$$

## (b) Operations Costs:

$$0.2 (\$_{QA} + \$_C) = .479 \times 10^6$$

## (c) Annual Equipment Costs:

$$0.1 (\$'_{TR} + 3.61 (\$'_{F1}) \times \$_{C1})$$

where,  $\$_{C1} = \$225,000$

4. The costs related to SD system are shown in Table VII and in Note 1. The changes in costs for this system are:

$$\$_A = \$1.87 \times 10^6 \text{ and } \$'_{F1} = \$0.065 \times 10^6$$

5. Costs are same as shown in Note 2 with the following exceptions:

$$\$_A = \$0.454 \times 10^6 \text{ (antenna system) and,}$$

$$\$'_{F1} = \$0.065 \times 10^6 \text{ (preamplifier)}$$

6. The costs are the same as shown in Note 3 with the following exceptions:

$$\$_{A1} = \$0.454 \times 10^6 \text{ (42 foot reflector)}$$

$$\$'_{F1} = \$0.065 \times 10^6 \text{ (1.0 db NF preamplifier)}$$

$$\$_{A2} = \$1.462 \times 10^6 \text{ (102 foot base and back-up structure).}$$

allocated to M&O costs were discussed in Chapter 4, Section 4.2, Cost Analysis Procedure, and consequently, will not require a lengthy discussion here. These assumptions will be stated where they are appropriate for sake of clarity.

For the present development the following assumptions are made:

(1) The existing mean-time-between-failure (MTBF) data for an earth station supporting a synchronous communication satellite system will be considered as the standard.

(2) Equipment failure will follow the exponential failure law.

(3) The replacement cycle of the system is keyed to the physical wear-out period of the antenna system, viz., 15 years.

(4) Annual equipment costs will be 10 percent of the electronic equipment investment costs and operations costs will be 20 percent of the station investment costs.

(5) Cost in increasing the availability of the system will also be exponential. The cost equation is derived from an approach similar to one suggested by Sandler.<sup>51</sup> The equation is as follows:

$$\$_I = \$_S [1 + e^{K(A_D - A_S)}] \quad (24)$$

where,

$\$_I$  is cost of equipment with improved availability in dollars,

$\$_S$  is cost of equipment with standard availability,

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<sup>51</sup>Gerald H. Sandler, System Reliability Engineering (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1963), p. 150.

$A_D$  is equipment availability required for system,

$A_S$  is equipment availability as achieved with state of the art components, and

$K$  is the ratio of mean-down-time of standard system to mean-down-time of required system; viz.,

$$K = \frac{D_S}{D_D} \quad (25)$$

where,

$D_S$  is steady-state down-time of standard system in hours, and

$D_D$  is steady-state down-time of desired system in hours.

(6) Recent GSFC study<sup>52</sup> indicates that the amount of reusable antenna equipment at the end of a technological life cycle can vary from 82 to 58 percent. In this development, the salvage value for all the systems considered will be assumed to be zero.

(7) The station will be located at GSFC.

(8) Radomes will not be considered

To meet the system availability requirement, the reliability of station equipment must be investigated. To perform a complete reliability analysis on the ground station equipment is beyond the scope of this effort. However, pertinent factors will be analyzed and adjustments in costs of equipment will be made.

Reliability data were compiled for a typical ground station supporting a synchronous communication satellite.<sup>53</sup> The numbers are representative of a station whose subsystem has survived a six month "burn-in" period and whose components are non-redundant and provide the required antenna effectiveness. Data for Table XIV below were derived from the data available and are used as a basis for the forthcoming analysis.

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<sup>52</sup> John E. Moye, Eula B. Paseur, and Philip B. Pease, Cost Effectiveness Analysis of Telemetry Data Acquisition by the Space Tracking and Data Acquisition Network (STADAN) (GSFC X-520-69-275, July 1969) p. 13.

<sup>53</sup> C. Louis Cuccia, Todd G. Williams, Phil R. Cobb, Allen E. Small, and James P. Rahilly, "RF Design of Communication Satellite Earth Stations Part III" (Microwaves, July 1967) p. 54.

Table XIV

## TDRS Ground Antenna Availability Data

Subsystem	MTBF (hrs)	Mean Down Time D (hrs)	Availability
Antenna	50,000	12	0.9998
Feeds	4,000	2	0.9995
Paramp Preamplifier	2,000	5.5	0.9972
Tracking Receiver	3,000	0.5	0.9998
Antenna Servo	2,500	0.5	0.9998
Control Consoles	2,000	0.5	0.9997
System Wiring	5,000	1.5	0.9997
		Total System <sup>(1)</sup>	0.9955 -

Note: 1. The data does not include the command system which will be discussed separately.

From the data available in Table XIV, it can be ascertained that the system will not achieve the required system availability of 0.998 with existing subsystem availability characteristics. Consequently, the critical subsystems which contribute the lowest availability figures to the system will have to be designed in such a way as to increase their availability to the extent that overall system availability requirements are met. The basic subsystem which needs to be redesigned is the preamplifier. Using Equations (24) and (25), the cost of the preamplifier will be modified to include the imputed cost of a more reliable preamplifier. To meet a 0.998 overall availability, the required preamplifier availability must be 0.9997. The value of K in Equation (25) becomes 11; that is, mean down-time must be reduced from 5.5 hours to 0.5 hours. Putting in the various values mentioned, Equation (24) becomes the following:

$$S_I = S_{F1}^* [1 + e^{11(0.9997 - 0.9972)}] = S_{F1}^* [2.028]$$

where,

$\$ _I$  = is cost of an improved amplifier in dollars, and

$\$ _{F1}^*$  = cost of preamplifier = ( $\$ _{F1} = \$65,000$  or  $\$ _{F1}^1 = \$80,000$ )

Evaluating the above,  $\$ _I$ , the adjusted cost of a paramp with the required availability, is  $\$162,000 = \$ _{F1}^1$  and  $\$132,000 = \$ _{F1}$ . Consequently, the cost of the single dish (SD) station will have to be adjusted to the following:

Item	Cost	
	With $\$ _{F1}$	$\$ \times 10^6$ With $\$ _{F1}^1$
Antenna and Receiver Costs	2.867	1.987
Annual Direct and Indirect Operations Costs	0.573	0.397
Annual Equipment Costs	0.049	0.052
Total Costs per antenna	$2.867 + 0.622Y$	$1.987 + 0.449Y$

In considering the quad-array (QA) antenna and the multiple aperture (MA) antenna system, the question of availability becomes somewhat involved. Figure 18 depicts curves of the parallel characteristics of the critical subsystems related to the QA and MA systems. For example, consider a preamplifier with an availability of 0.8. From the curves given in Figure 18, the QA and MA systems can still meet the availability requirements whereas the SD system cannot. Thus, QA and MA systems can readily achieve the system availability requirements without incurring additional expense of developing super reliable preamplifier components or developing a redundant standby system. It should be noted, however, that the QA and MA systems will not be as available as the SD system to meet full operational requirements of say 70 db. This is due to the fact that all the antenna elements are necessary for full operation; consequently, arrays must be treated in a series fashion. Further discussion regarding the trade-off between gain and availability will be deferred to Chapter 6.

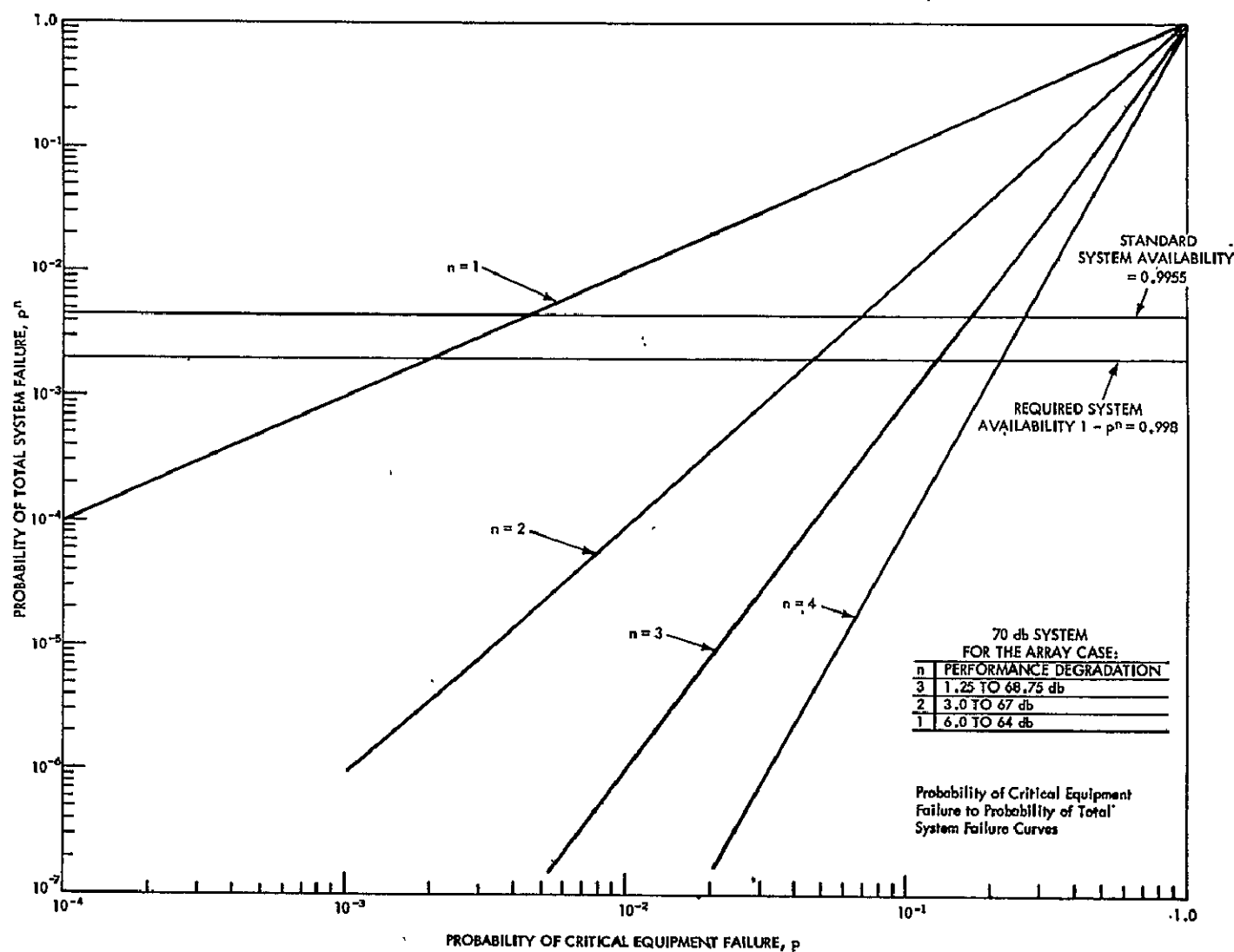


Figure 18. Probability of Critical Equipment Failure  
To Probability of Total System Failure Curves

In developing the total systems costs, one additional cost which occurs in the MA system is the cost for time delay equipment. This equipment is necessary to compensate for the different signal arrival times occurring at each aperture as a function of antenna elevation angle. The estimated cost for this equipment is \$225,000.

The cost of the command system (\$735,000) is included in the total investment for each type of station configuration. The overall availability of the command system was determined to be 0.997 (see Appendix B.2 for tabulation of reliability factors). This performance figure was assumed to be acceptable; consequently, no redundancy costs are included and only standard costs are used in the forthcoming analysis. Table XV is a tabulation of the total station costs for the three TDRS ground station configuration for the two receiving systems considered.

Because of the common life cycle, the pattern of investment recovery for the various configurations can be readily compared by using the present worth (PW) principle/equivalent annual cost (EAC) principle. The EAC can be found by converting PW to equivalent series of equal end-of-period payments.<sup>54</sup>

The PW equation is given by the following formula:

$$PW = I - \frac{S^*}{(1+i)^n} + \sum_{n=1}^n \frac{AOC}{(1+i)^n} \quad (26)$$

where,

PW is present worth of investment recovery, interest costs and operating costs in dollars.

I is initial investment in dollars,

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<sup>54</sup>William T. Morris, The Analysis of Management Decisions (Homewood, Illinois: Richard D. Irwin, Inc. Rev. Edition, 1964) p. 57.

Table XV

Total Station Cost Data on Three Types of Ground Antenna  
Systems for Two Different Receiving Systems

## Costs

Station Configuration <sup>(1)</sup>		Initial Investment (I) X 10 <sup>6</sup> (dollars)	Annual Operating (AOC) X 10 <sup>6</sup> (dollars)
Single Dish (SD) Station	Rec. Syst. 0.5 db NF	1.987	0.449
	Rec. Syst. 1.0 db NF	2.867	0.622
Multiple-Aperture (MA) Station	Rec. Syst. 0.5 db NF	3.14	0.749
	Rec. Syst. 1.0 db NF	3.3	0.776
Quad-Array (QA) Station	Rec. Syst. 0.5 db NF	2.39	0.546
	Rec. Syst. 1.0 db NF	2.65	0.593

Note: 1. The equipment life cycle is 15 years.



$S^*$  is salvage value for the three systems studied; thus  $S^* = (S_{SD} \text{ or } S_{MA} \text{ or } S_{QA}) = \text{zero}$ .

AOC is annual operating cost in dollars/year,

$n$  is 15 (life cycle) in years, and

$\frac{1}{(1+i)^n}$  is discount rate and  $i = 0.1$

The EAC equation is given by the following formula:

$$EAC = (I - S^*) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] + iS^* + \left( \sum_{n=1}^n \frac{AOC}{(1+i)^n} \right) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (27)$$

The terms in Equation (27) were defined previously.

Using Equations (26) and (27), the investments are analyzed; the results are presented in Tables XVI and XVII. Table XVI shows the PW and EAC for system using a 0.5 db NF receiving system and Table XIX shows the same cost functions for a 1.0 db NF receiving system.

**Cost-Benefit Study – ROI and BEP Analysis:** With the introduction of the TDRS Network, certain operational expenses related to the GSFC network operation will be reduced; thus, annual savings in network station operation will accrue. These savings can be used in calculating the rate of return on the investment associated with the installation of a TDRS ground antenna. Data on network operations were obtained from internal GSFC documents which are referred to below. The following guidelines are used in establishing ROI and BEP:

(1) All antennas and tracking receivers in the phased-out ground stations will be regarded as having no salvage value; thus, station equipment will be considered as sunk costs.

Table XVI

Results of Present Worth (PW) and Equivalent  
Annual Cost (EAC) Analyses for the Single  
Dish, Quad-Array and Multiple-Aperture Ground Station Configurations  
for Receiving System with a 0.5 db NF (68.5 db System Gain)

Decision Models	Antenna Configurations		
	Single Dish (SD) Station \$ X 10 <sup>6</sup>	Multiple-Aperture (MA) Station \$ X 10 <sup>6</sup>	Quad-Array (QA) Station \$ X 10 <sup>6</sup>
<b>1. <u>Present Worth Principle</u></b>  Present Worth of investment recovery and interest costs  $I - \left( \frac{S^*}{(1+i)^n} \right)$	1.987	3.14	2.39
PW of Operating Costs  $\sum_{n=1}^{15} \frac{AOC}{(1+i)^n}$	3.42	5.7	4.15
<b>Total Present Worth</b>	<b>5.407</b>	<b>8.84</b>	<b>6.54</b>
<b>2. <u>Equivalent Annual Cost Principle</u></b>  EAC of investment recovery and interest cost  $(I - S^*) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] + iS^*$	0.262	0.415	0.316
EAC of Operation  $\left( \sum_{n=1}^{15} \frac{AOC}{(1+i)^n} \right) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right]$	0.451	0.752	0.548
<b>Total Equivalent Annual Cost</b>	<b>0.713</b>	<b>1.167</b>	<b>0.864</b>

Table XVII  
Results of Present Worth (PW) and Equivalent  
Annual Cost (EAC) Analyses for the Single  
Dish, Quad-Array and Multiple-Aperture Ground Station Configurations  
for Receiving System with A 1.0 db NF (70 db System Gain)

Decision Models	Antenna Configurations		
	Single Dish (SD) Station \$ X 10 <sup>6</sup>	Multiple-Aperture (MA) Station \$ X 10 <sup>6</sup>	Quad-Array (QA) Station \$ X 10 <sup>6</sup>
<b>1. <u>Present Worth Principle</u></b>  Present Worth of investment recovery and interest costs  $I - \left( \frac{S^*}{(1+i)^n} \right)$	2.867	3.30	2.65
PW of Operating Costs  $\sum_{n=1}^{15} \frac{AOC}{(1+i)^n}$	4.73	5.90	4.51
<b>Total Present Worth</b>	<b>7.597</b>	<b>9.2</b>	<b>7.16</b>
<b>2. <u>Equivalent Annual Cost Principle</u></b>  EAC of investment recovery and interest cost  $(I - S^*) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] + iS^*$	0.379	0.435	0.350
EAC of Operation  $\left( \sum_{n=1}^{15} \frac{AOC}{(1+i)^n} \right) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right]$	0.625	0.780	0.595
<b>Total Equivalent Annual Cost</b>	<b>1.004</b>	<b>1.215</b>	<b>0.945</b>

(2) Expenses being reduced will be related only to reduction of the number of people being employed, furthermore, only those people who are involved directly with the antenna operation and maintenance and with the tracking receiver operation and maintenance are considered as appropriate cost elements to be charged off against the TDRS ground antenna investment.

(3) Using Guideline (2), the following people costs will be considered as legitimate write-off expense to TDRS ground antenna system:

(a) costs of two technical operators: antenna control console operator and a receiver operator.

(b) costs of two technical maintenance and repair people: servo drive mechanic and receiver electronic technician.

(4) The stations are assumed to operate on a two-shift basis.

(5) The average salary of the station personnel is taken to be \$13,000 per annum;<sup>55</sup> however, a 10 percent upward adjustment to this figure is assumed as an updated estimate for this analysis.

(6) Three ranges of network reductions will be considered.<sup>56</sup> These are the following:

(a) STADAN Reductions

Upper Range - Phase out 9 of 15 existing stations

Middle Range - Phase out 8 of 15 existing stations

Lower Range - Phase out 7 of 15 existing stations

(b) MSFN Reductions

Upper Range - Phase out 7 of 13 existing stations

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<sup>55</sup> Moyer, et al, Cost Effectiveness Analysis of Telemetry Data Acquisition by the Space Tracking and Data Acquisition Network (STADAN) (GSFC X-520-69-275, July 1969), p. 21.

<sup>56</sup> Gruhl, et al, Tracking and Data Relay Satellite Network (TDRSN) Cost and Benefit Study (GSFC X-264-69-526, Dec. 1969), pp. 21, 22.

Middle Range - Phase out 6 of 13 existing stations

Lower Range - Phase out 5 of 13 existing stations

Table XVIII shows the annual savings in operational costs for the three ranges of station reduction considered.

Table XVIII  
Savings in Antenna System Operations With the  
Retirement of Certain MSFN and STADAN Stations

Range of Network Reduction	Station Personnel			Equivalent Annual Savings (EAS) \$ X 10 <sup>6</sup>
	STADAN	MSFN	TOTAL	
Upper	28	56	84	1.20
Middle	21	49	70	1.00
Lower	13	40	58	0.88

To determine the rate of return on the investment, the stream of costs and savings should be such that at a certain discount rate the present worth of the investment is equal to zero. This discount rate establishes the rate of return on the investment. Mathematically, this concept can be expressed as:

$$EAS \left[ \frac{(1+i)^n - 1}{i(1+i)^n} \right] - PW = 0 \quad (28)$$

where, EAS is equivalent annual savings in dollars, expression in the

brackets is the "end-of-period payments" factor, and

PW is present worth of investment.

n is the life of investment in years; n = 15.

Rearranging and combining terms, Equation (28) can be rewritten as:

$$MR^{16} - (M+1)R^{15} + 1 = 0 \quad (29)$$

where,

M is the ratio of PW/EAS,

R is equal to  $(1 + i)$

Tables XIX and XX presented below summarize the findings of the ROI analysis for the two system gains considered. Table XIX gives the results for the 68.5 db system and Table XX gives the results for the 70 db system.

Table XIX

Results of ROI Analysis for 68.5 db System

	EAS \$ X 10 <sup>6</sup>	ROI (%)			PW at 10% (\$ X 10 <sup>6</sup> )			Ratio of PW at 10% to Investment		
		SD(1)	MA(2)	QA(3)	SD	MA	QA	SD	MA	QA
Upper	1.20	21.0	10.8	17.0	3.73	0.30	2.60	0.69	0.03	0.40
Middle	1.00	17.0	7.5	12.8	2.20	-1.23	1.07	0.41	—	0.16
Lower	0.83	12.8	4.7	9.8	0.91	-2.52	-0.22	0.17	—	—

- Notes: 1. Total investment in the single dish (SD) station is  $1.987 \times 10^6$  dollars plus  $0.449 \times 10^6$  dollars in annual operation costs.
2. Total investment in the multiple-aperture (MA) station is  $3.14 \times 10^6$  dollars plus  $0.749 \times 10^6$  dollars in annual operation costs.
3. Total investment in the quad-array (QA) station is  $2.39 \times 10^6$  dollars plus  $0.546 \times 10^6$  dollars in annual operation costs.

Table XX

Results of ROI Analysis for 70 db System

	EAS \$ X 10 <sup>6</sup>	ROI (%)			PW at 10% (\$ X 10 <sup>6</sup> )			Ratio of PW at 10% to Investment		
		SD(1)	MA(2)	QA(3)	SD	MA	QA	SD	MA	QA
Upper	1.20	13.4	10.0	15.0	1.54	0.00	2.00	0.20	—	0.28
Middle	1.00	10.0	6.7	11.2	0.00	-1.60	0.44	—	—	0.06
Lower	0.83	7.0	4.0	8.0	-1.28	-2.88	-0.84	—	—	—

Table XX (continued)

- Notes: 1. Total investment in the single dish (SD) station is  $2.867 \times 10^6$  dollars plus  $0.622 \times 10^6$  dollars in annual operation costs.
2. Total investment in the multiple-aperture (MA) station is  $3.3 \times 10^6$  dollars plus  $0.776 \times 10^6$  dollars in annual operation costs.
3. Total investment in the quad-array (QA) station is  $2.65 \times 10^6$  dollars plus  $0.593 \times 10^6$  dollars in annual operation costs.

The break-even point (BEP) is defined as the point on the investment curve which is equal in value to a point on the accrued savings curve at the same time in the life cycle of the system. The curves showing various BEP's for the three network configurations, for the three network reductions plans and for a 68.5 db system gain are given in Figure 19. The same curves are presented in Figure 20 for a 70 db system gain.

Summary of The Results of the Cost-Benefit Analysis: From a study of the results of the analysis, several comments seem appropriate:

(1) Present Worth and Equivalent Annual Cost Values. From Table XVI, it can be seen that the SD system has the lowest PW and EAC for the system gain requirement of 68.5 db. From Table XVII, it can be observed that the QA system has the lowest PW and EAC values for the system gain requirement of 70 db. Thus, as higher gain requirements are imposed on the system, the QA system becomes more economical than the SD system. This result correlates closely with the findings made in the CE analysis. It should be noted also that the MA system's PW and EAC values change about 4 percent for the two system gain requirements. Thus, the cost function of the MA system is virtually insensitive to system effectiveness. This result also correlates well with the results obtained from the CE analysis. In the CE analysis (see Figure 12), it was found that the MA system had an increasing CE value beyond the system gain of 74.3 db; thus, the MA system did not reach an optimum CE value in

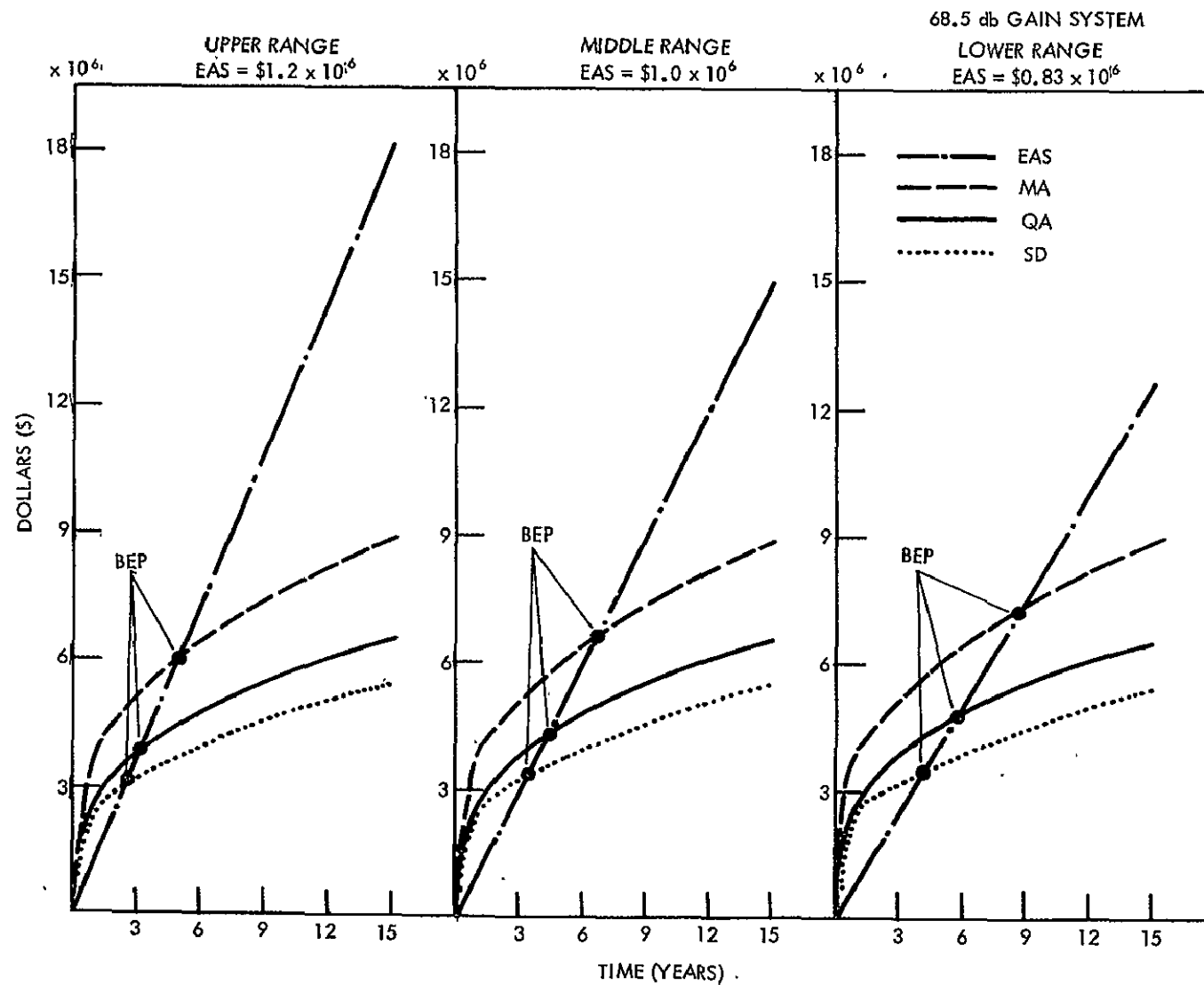


Figure 19. BEP Curves for the SD, MA and QA Systems for Three Annual Savings Values and for a 68.5 db System Gain



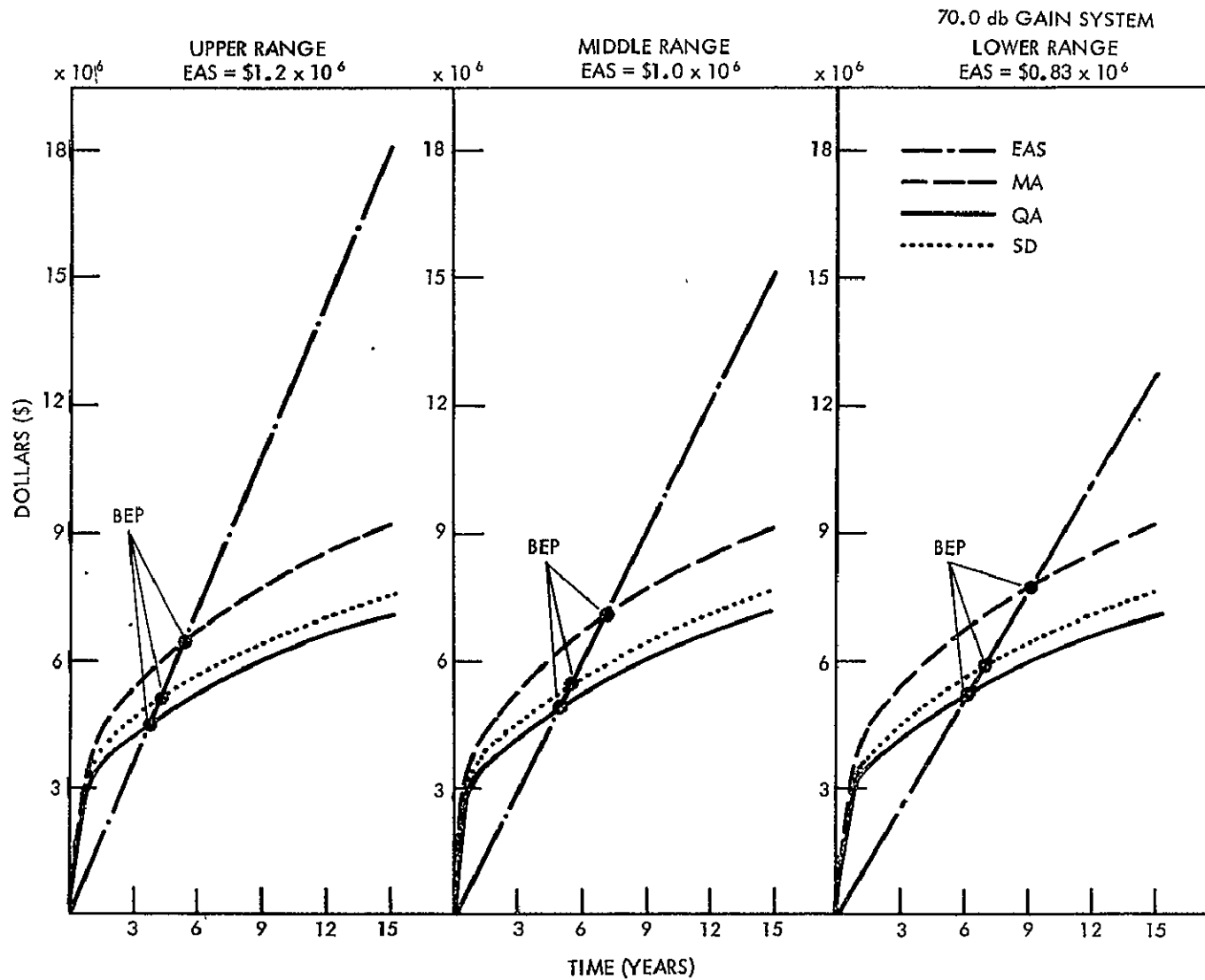


Figure 20. BEP Curves for the SD, MA and QA Systems for Three Annual Savings Values and for a 70 db System Gain

this study. Consequently, the MA system will fare poorly for the range of interest required in this investigation. Other comments related to the MA system are deferred to Chapter 6.

(2) ROI and BEP Analysis. From Table XIX, it can be observed that the highest ROI for a receiving system requiring an antenna gain of 68.5 db is realized by the employment of an SD system. This characteristic of the system can be verified by scanning the PW and EAC values shown in Table XVI. The data of the ROI analysis, shown in Table XIX also indicate that the SD system is the preferred configuration for all three station reduction programs considered.

From Table XX, it can be observed that the QA system gives the best ROI for a receiving system requiring an antenna gain of 70 db; however, percentage of ROI is lower for the 70 db gain system than for the 68.5 db gain system. Table XX also shows that the least cost-benefit station is the MA system. The ROI analysis points up the insensitivity of the MA system to changes in the system gain requirements. This behavior was discussed in comment (1).

The BEP analysis shows that the SD system recovers its investment the earliest of the three systems considered for a receiving system which requires an antenna gain of 68.5 db. The results shown in Table XX imply that the QA system has the highest investment recovery rate of the three systems for the 70 db antenna gain requirement. The MA system yields less than ten percent return for the two lower ranges of station reduction considered.

## CHAPTER 6

### DEVELOPMENT OF OPTIMUM TDRS GROUND SYSTEM MODELS

In Chapter 5, cost-effectiveness (CE) analysis was performed on three antenna configurations; these were: the single dish (SD) system, the multiple-aperture (MA) system, and the quad-array (QA) system. The analysis included consideration for two different system gain requirements, viz., the 68.5 db and the 70 db antenna gain requirements. In addition to the CE analysis, an economic analysis was performed on the TDRS station investment and operation for the three station models developed and for the two system gain requirements considered. The economic analysis resulted in establishing values for the return-on-investment (ROI) and the break-even point (BEP) for different levels of savings possible.

In this chapter, the results of the analyses will be explored in greater depth to determine reasons and to assign causes for certain system behavior. Thus, by developing the etiological base, a rational judgement basis can be established for making more effective engineering management decisions. The procedure that will be followed is: (a) study of antenna models to develop the maximum CE antenna system, and (b) study of station configurations to determine the maximum cost-benefit TDRS ground station.

#### 6.1 Maximum Cost-Effectiveness Antenna Model

The CE analysis, which is related to the 68.5 db gain antenna system, indicates that the SD system has the highest CE value followed closely by the QA system. The MA system has the lowest CE value; see Figure 14. The reason why the MA system compares so poorly to the other two systems can be determined from an

examination of the cost model, equation (16). It can be seen that the cost of the electronic package associated with the antenna rises in direct proportion with the antenna cost. Thus, as long as the antenna requirements do not force the system to choose diameters near the gain-limit point, the single dish costs will not increase as rapidly as the MA costs. Another consideration which seriously derates the CE value of the MA system is its bandwidth capability. Since separation between array elements determines the array bandwidth, any significant distance separating the array elements will seriously limit the bandwidth. As previously mentioned, the required bandwidth of the TDRS ground system is 2 GHz at 16 GHz. From geometric considerations, the array elements should be edge-to-edge, but to prevent "shadowing" of elements, i.e. elements blocking the view of other elements, a separation of 175 feet is required. Consequently, such technical difficulties impose heavy cost-penalties on the MA system in order to meet system requirements.

The CE analysis related to the 70 db gain antenna system indicates that the QA system is slightly more cost-effective than the SD system and that the MA system is 30 percent less cost-effective than the QA system. The closeness of the QA and SD systems in CE can be attributed to the fact that system effectiveness and the incremental change in system costs coincide at the required system performance level. From Figure 15, it can be seen that the slope of the SD system's CE curve is negative and the slope of the QA system's CE curve is positive, consequently, the order of preference of systems should be made in light of future system gain requirements.

To show how certain system parameters affect the cost of the system, the following heuristic analysis is presented. The term antenna effectiveness (AE) was defined as the ratio of the gain of the antenna to the system noise temperature (see Equation 6).

For sake of mathematical simplicity, it is assumed that the cost of the antenna follows a power law relationship and is of the form given in Equation (8). The antenna effectiveness formula can then be written as:

$$AE = \frac{\eta a_4^2 f^2 \left(\frac{\$}{R}\right) \frac{2}{b} e^{-(a_5 f \sigma)^2}}{T_s} \quad (30)$$

where,

AE is antenna effectiveness in gain (absolute units) per °K

\$ is RD<sup>b</sup> in dollars

R is a constant 4.37 taken from a JPL study, (see reference 17)

b is a constant 2.78 taken from the same JPL study

D is diameter in feet

T<sub>s</sub> is system noise temperature in °K

σ is surface tolerance in millimeters

a<sub>4</sub> is a constant, 3.20

a<sub>5</sub> is a constant 4.19 × 10<sup>-2</sup>

f is the operating frequency, taken at 16 GHz

η is antenna efficiency

The total derivative of AE can be written as:

$$d(AE) = \frac{\partial(AE)}{\partial \$} d\$ + \frac{\partial(AE)}{\partial T_s} dT_s + \frac{\partial(AE)}{\partial \sigma} d\sigma + \frac{\partial(AE)}{\partial \eta} d\eta \quad (31)$$

It is assumed that the surface tolerance, σ, is fixed by the criterion established for the GSFC model, i.e. σ = 3.6 × 10<sup>-4</sup> D. Thus, for a specified operating frequency, the antenna effectiveness is fixed i.e. d(AE) = 0. Equation (31) can be rearranged to form the following relationship:

$$\frac{d\$}{\$} = \frac{b}{2} \left[ \frac{dT_s}{T_s} - \frac{d\eta}{\eta} \right] \quad (32)$$

where,

$b/2$  is 1.39.

Equation (32) implies that changes in antenna efficiency and system noise temperature can be related to change in antenna cost. For example, an increase of efficiency of 0.6 to 0.7 could result in savings by reducing the antenna size without a corresponding reduction in the required antenna performance. The cost reduction in this case would be approximately 22 percent. Furthermore, a reduction in system noise temperature by 25 percent would reduce antenna cost by 35 percent. Thus, it can be seen that development of a more efficient feed and/or the development of a receiver with an improved noise figure can impact substantially the economic considerations related to the design of a TDRS ground antenna system. From the cost-effectiveness standpoint, therefore, the antenna system having a preamplifier with the lowest noise figure practical should be selected.

## 6.2 Maximum Cost-Benefit Station Model

As previously mentioned, the SD system has the lowest PW and EAC for the system gain requirement of 68.5 db, see Table XVI; and, the QA system has the lowest PW and EAC values for the system gain requirement of 70 db, see Table XVII. Comments appropriate to the stated results have been made in the summary section associated with the cost-benefit presented in Chapter 5.

Based on the economic factors alone, it appears that for the 68.5 db gain system a decision maker should select the SD station configuration. However, the system behaves under

environmental conditions not clearly predictable; therefore, the situation is not, in the OR sense, an obvious case of decision under certainty. Indeed, the system performance specifications must be interpreted in light of operational realities. Specifically, the TDRS ground station will be a single installation; as such, a firm requirement exists for continuous access and continuous service capabilities. Availability, therefore, should be weighed very heavily. Another fundamental requirement for the TDRS ground antenna is system gain. The rationale leading to the system gain requirements stems from the fact that receiver signal strength should have at least a 20 db carrier-to-noise-ratio (CNR) for 99.8 percent of the "operational time." The "operational time" of the system is defined as the time the system is required to participate in tracking, receiving and for transmitting signals. The 30 db CNR used in calculating the required antenna gain takes into account the "worst-case" atmospheric conditions, i.e., operations under heavy rainfall.

Table XXI below summarizes the "worst case" operational conditions for the TDRS ground station.

Table XXI

Probability Data on Worst Case Operating Conditions for the TDRS  
Ground Station Located in the Vicinity of Washington, D.C.

Elevation Angle (degrees)	CNR (db)	Percentage of Occurrence of 10 db Loss	
		Receiver NF = 0.5 db	Receiver NF = 1.0 db
20	20	0.9	0.5
15	20	1.8	1.3
Elevation Angle (degrees)	CNR (db)	Percentage of Occurrence of 20 db Loss	
		Receiver NF = 0.5 db	Receiver NF = 1.0 db
20	10	0.03	less than 0.03
15	10	0.12	0.1

From the above table it can be seen that the system will meet its full operational requirements more than 98 percent of the time with a 10 db gain margin to spare. Consequently, it would seem justifiable to assume that a loss of antenna gain of 2 or 3 db normally would not be significantly detrimental to its operation. One conclusion that can be drawn from the discussion is that a decision maker would be wise to use a utility curve which would trade off a relatively large decrease in system gain to realize a small increase in system availability. Pursuing that line of reasoning it would be, therefore, more attractive to select the QA station on the grounds of greater utility. Figure 18 contains data which implies that the QA station is much less likely to have a catastrophic failure, i.e. zero availability, than the SD station.

To summarize the above discussion, it can be stated that for a system gain requirement of 68.5 db the QA station is more costly to operate and the initial outlay of capital is greater than for the SD station. The benefits, however, of the QA station in essence are as follows:

(1) Portion of the antenna can be serviced while the antenna is in operational status; thereby, reducing the mean-down-time to zero and thus, providing a station availability of 100 percent. The probability that all four antenna/receiver systems will fail at the same time is infinitesimally small.

(2) Operational flexibility is easily attainable. Through the use of conventional phase control networks, beam pointing as an acquisition and tracking aid can be readily accomplished.

For a system gain requirement of 70 db, the QA station yields a higher ROI; moreover, for operational benefits mentioned above and for potential savings benefits in the future when system gain requirements are increased, the QA system is preferable.



The MA system has not been prominently mentioned in the above discussion because results presented in Chapter 5 and the presentation in Chapter 6, Section 6.1 clearly disqualify it from further serious consideration.

## SUMMARY

### Discussion of Results

The point and purpose of this study was to formulate a systematic procedure for analyzing the requirements of a prototype ground tracking station to be used in conjunction with a geostationary tracking and data relay satellite network. The methodology devised consisted of the following process: (a) the establishment of a frame of reference, i.e. a rationally founded criterion of system effectiveness, to enable one to examine the essential features of competing systems in a quantitative way, and (b) the ascertainment of relative worth of trading-off one set of system characteristics for another in light of the established criterion.

To focus sharply on the systems analysis procedure, only three basic configurations were selected as candidates for the best technical solution. The three TDRS ground antenna configurations are as follows:

(1) Single Dish (SD) Antenna. A single reflector mounted on a gimbaled pedestal capable of rotating in two axial planes of motion.

(2) Quad-Array (QA) Antenna. An array of four reflectors mounted on a single pedestal; this antenna is also capable of bi-axial motion.

(3) Multiple Aperture (MA) Antenna. An array of four reflectors; each reflector, however, is mounted on a separate bi-axial pedestal identical to configuration (1).

The configurations were analyzed for two different system gain requirements; a 68.5 db and a 70 db gain requirement.

Within the milieu of restrictions imposed arbitrarily and physically, certain important features of the TDRS ground station analysis were noted. These characteristics are:

(1) Atmospheric Influences. Because the environmental conditions play a critical role in determining the reflector performance, special consideration was given to the study of radomes and their affect on system performance. It was found that attenuation and water run-off problems during a heavy rain were severe enough so that the use of a radome was considered an impractical solution to the problem.

(2) Limitations of the MA System. The insensitivity to system costs; the low CE values and the high PW's and EAC's; the additional burden on station availability imposed by the time delay unit; and, the serious restrictions on system bandwidth as a result of a large separation distance between array elements disqualifies the MA system from serious contention in the competition for the selection of the TDRS ground station configuration.

(3) Twin Performance of the SD and QA Systems. The CE curves show that the behavior characteristics of the two systems are essentially the same for the two system gain requirements considered, see Figures 14 and 15. Since the QA system operates with smaller reflectors, the efficiency of the aperture is increased; consequently, the QA system is capable of higher gains than the SD system. The result of this behavior is a lateral shift of the QA system's CE curve. The maximum CE value for the QA system occurs at the 71.5 db gain point for the 68.5 db gain system and for the 70 db gain system. The maximum CE value for the SD system is 68.5 db for both system gain requirements considered. Although some savings accrue because smaller reflectors are used in the QA system, these savings are largely offset by the multiplier effect associated with the electronics.

All things considered, the results of the trade-off analysis showed that the QA and SD antennas were the most cost-effective of the three potential designs studied. Considering the economics related to annual operation costs and the initial investment of capital, the station configuration giving the most for the money, for a system gain

requirement of 68.5 db, is the SD station. However, when a rational utility curve is applied to the "availability-gain" relationship, a decision-maker's choice could become heavily biased toward the QA station.

### Concluding Remarks

The basic set of assumptions for the study were presented in Chapter 1, and whenever the subject development required the use of informational data which was uniquely suited to the particular presentation, additional assumptions were stated explicitly. However, above and beyond these assumptions several additional restrictions should be noted. These assumptions are the following:

(1). The TDRS Network will be optimally deployed in the following sense: only one TDRS ground station will be required. Specifically, the costs associated with station installation and operation have been confined to the case of a single ground station located near GSFC, Greenbelt, Maryland. If after a study of network deployment schemes,<sup>57</sup> it is deemed advisable to install two or more TDRS ground stations, a more extensive cost-effectiveness study would have to be initiated.

(2) No attempt has been made to take into account technological breakthrough in the field of laser communications. Obviously, one cannot ignore changes coming from the laser research and equipment development direction. However, for the purpose of this study the attention was focused on concepts amenable to establishment of adequate scales by which alternatives can be measured. Therefore, only radio communication links were considered.

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<sup>57</sup> Dale L. Fahnestock, A Study of Tracking and Data Relay Satellite Network Deployments (GSFC X513-70-100, April 1970), pp. 6-24.

(3) No attempt has been made to adjust the cost models to take into account GNP growth and the inflationary trend of the nation's economy.<sup>58</sup> The reason for this assumption is the following. It is believed that the primary intent of cost models is not precision, although they should indeed reflect the prevailing range of costs in the elements involved; the primary purpose of models is to compare the models in relation to one another.<sup>59</sup> Thus, the relative cost is the true yardstick for comparison rather than some absolute scale.

With these remarks in mind, it is believed that procedure developed will be useful in analyzing similar systems; it is a methodological french curve to effectively interlink judgment, knowledge and experience to the analysis of systems problems. The methodology was never intended to generate pat solutions universally applicable.

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<sup>58</sup>James W. Knowles Dir., U. S. Economic Growth to 1975: Potentials and Problems (Wash., D.C., U. S. Govt. Printing Office, 1966), p. 1-3.

<sup>59</sup>Milton A. Margolis and Stephen M. Barro, "The Space Program" in David P. Novick Editor, Program Budgeting, Program Analysis and the Federal Budget Cambridge, Mass., Harvard University Press 1965), pp. 133-135.

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## APPENDIX A

### FACTORS RELATED TO ANTENNA EFFECTIVENESS

Antenna Effectiveness is a critical figure of merit in an antenna design. It relates antenna area to system noise temperature. To show how noise, efficiency, and gain are related, consider the gain formula for a circular aperture. The expression for a parabolic reflector is as follows:

$$G = \frac{\eta 4 \pi A}{\lambda^2} = \frac{\eta \pi^2 D^2}{\lambda^2} = \eta \left( \frac{\pi D}{\lambda} \right)^2 \quad (\text{A.1})$$

where,

G = antenna gain in absolute units,

$\eta$  = antenna efficiency (ratio of practical to theoretical gain),

A = aperture area feet-squared,

D = antenna diameter in feet, and

$\lambda$  = wavelength in feet

Antenna effectiveness is given by the following formula:

$$AE = \frac{G}{T_s} = \frac{\eta}{T_s} \left( \frac{\pi D}{\lambda} \right)^2 \quad (\text{A.2})$$

where,

AE = antenna effectiveness in db/°K

$T_s$  = system noise temperature in °K

System noise temperature is the total thermal noise produced by the antenna and the receiving system. The mathematical expression (neglecting terms related to amplifier stages beyond the 1st) is:

$$T_s = \alpha T_A + 290 (1 - \alpha) + 290 (NF - 1) \quad (A.3)$$

where,

$T_s$  = system noise temperature in degrees Kelvin ( $^{\circ}\text{K}$ )

$T_A$  = antenna effective noise temperature in  $^{\circ}\text{K} = 280 (1 - \alpha_1) + T_1$

$T_1$  = antenna noise temperature (mainly due to spillover taken to be  $10^{\circ}\text{K}$ )

$\alpha$  = transmission line coefficient for the line between antenna and preamplifier

$\alpha_1$  = attenuation coefficient due to the atmosphere

NF = noise figure of 1st preamplifier

For the study,  $\alpha = .89$ ,  $T_1 = 10^{\circ}\text{K}$  for a clear sky, and NF = 0.5 db (cooled paramp front-end) and NF = 1.0 db for uncooled paramp front-end.

The total system noise temperature may be expressed as follows:

$$T_{\text{sys}} = T_{\text{sky}} + T_{\text{rad}} + T_{\text{ant}} + T_{\text{rec}} \quad (A.4)$$

$T_{\text{sys}}$  = total system noise temperatures in  $^{\circ}\text{K}$

$T_{\text{sky}}$  = tropospheric and extraterrestrial noise

$T_{\text{rad}}$  = radome noise due to lossy material and energy scatter

$T_{\text{ant}}$  = antenna noise due to feed spillover, scattering and resistive loss

$T_{\text{rec}}$  = receiver noise which comes from the receiver temperature and transmission line loss

# DISCUSSION RELATED TO THE EFFECTS OF RADOME ON GAIN AND NOISE TEMPERATURE

The mathematical expression for system noise temperature including radome effects is:

$$T_{SR} = \alpha_T T_A + T_{rad} \alpha + 290 (1 - \alpha) + 290 (NF - 1) \quad (A.5)$$

where,  $\alpha_T$  is  $\alpha_r \cdot \alpha$ . The term  $\alpha_r$  = radome attenuation coefficient; the term  $\alpha$  has been defined in equation (A.3).

Basically, the radome attenuation coefficient depends on two factors: one, the loss due to the inclusion of a membrane material in the transmission path, where the losses are primarily ohmic and reflective, and two, the loss due to blockage by the space frame. In addition to these losses, there also exists losses due to effects of water on the radome during a rain. The water effect also contributes to the noise temperature of the system. This contribution is mainly a function of the water film thickness present on the radome during a rain. Table A.1 below, summarizes the radome effects on the system as a function of sky conditions.

TABLE A.1  
Tabulation of Factors Related to Gain and Radome Noise Temperature

Sky Conditions	System Gain Loss (db)	$\alpha_r$	$T_{rad}$ (°K)
Clear	1.05	0.785	negl.
Light rain — 0.25 mm/hr	1.75	0.668	37
Moderate rain — 2.5 mm/hr	3.75	0.422	81
Heavy rain — 25.0 mm/hr	13.65	0.043	120

## APPENDIX B

### LINK CALCULATIONS FOR TDRS COMMAND SYSTEM

Space Loss	-208.8 db
Atmospheric Loss @ 30° elevation (clear sky)	- 0.2 db
Noise Power @ $T_s = 4500^\circ\text{K}$ , 5 MHz BW, NF = 12 db	- 95.0 dbm
Gain of Spacecraft antenna 4 ft. @ 45% efficiency	+ 42.7 db
Spacecraft losses ( $\alpha = .56$ )	- 2.5 db
CNR	- 73.8 db
Required CNR	+ 30.0 db
<hr/>	
Total EIRP required by TDRS ground station	-103.8 db
<hr/>	
Transmitted power 1 KW	+ 60.0 dbm
Antenna gain 6 ft @ 55% efficiency	+ 47.0 db
Line Losses ( $\alpha = .60$ )	- 2.2 db
<hr/>	
Total EIRP	+104.8 dbm
Gain Margin	1.0 db

#### $T_s$ Calculations

$$T_s = T\alpha + 290 (1 - \alpha) + (NF - 1) 290$$

$$T = 290$$

$$\alpha = .56$$

$$NF = 12 \text{ db}$$

$$T\alpha = 162^\circ\text{K}$$

$$290 (1 - \alpha) = 127^\circ\text{K}$$

$$290 (NF - 1) = 4200^\circ\text{K}$$

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$$T_s = 4489^\circ\text{K} \approx 4500^\circ\text{K}$$

Table B.1

Tabulation of Reliability Factors Associated  
With the TDRS Command Antenna<sup>(1)</sup>

Subsystem	MTBF (hrs)	Mean Down Time, D (hrs)	Availability A <sub>j</sub>
1. Antenna	50,000	12	0.9998
2. Feeds	4,000	2	0.9995
3. Transmitter <sup>(2)</sup>	1,500	2	0.9987
4. Exciter	2,500	0.5	0.9998
5. Servo	2,500	0.5	0.9998
6. Control Consoles	2,000	0.5	0.9997
7. System Wiring	5,000	1.5	0.9997
Total System Availability			0.997

Notes: 1. Data for calculating the availability values were obtained from the following source:  
C. Louis Cuccia, et al, "RF Design of Communication Satellite Earth Stations, Part III" (Microwaves, July 1967), p. 54

2. Since the transmitter has the lowest reliability value of all the subsystems considered, the obvious direction in system availability improvement is to make the transmitter a redundant system or improve transmitter component reliability.